Flood Frequency Analysis of King County Rivers with an Emphasis on the January 2009 Floods

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King County

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Flood Frequency Analysis of King County Rivers with an Emphasis on the January 2009 Floods

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EXECUTIVE SUMMARY

Flooding poses significant threats to public health and safety, transportation corridors and economic activities throughout King County. The County has experienced 12 federally declared flood disasters since 1990, and tens of thousands of county residents commute through, live, and work in floodplains.

Flood hazard assessments in King County (and throughout the United States) are based on analysis of flow data from continuous flow monitoring locations (typically those with at least 10 years of data) or are extrapolated to other locations based on the observed flow records. The flow data analysis is typically performed on records of peak discharge from an annual time series of peak discharges in what is termed a flood frequency analysis. The result of the flood frequency analysis is an estimate of the annual exceedance probability (AEP) of various flow magnitudes. The flood frequency analysis also estimates the *return period* or *recurrence interval*, which are essentially the inverse of the AEP. For example, an annual peak flow with an AEP of 0.01 or 1 percent (i.e., a 1 percent chance of occurring in any given year) is equivalent to a 100-yr recurrence interval flow. Because the flow record is routinely updated as new annual peak flow data are collected, flood frequency estimates can change – especially after an extremely large flood event.

The focus of this report is to update the flood frequency analyses on rivers with mapped floodplains reported in 2009 that provided a preliminary assessment of the January 2009 flood event that affected much of western Washington. This report also provides updated flood frequency analyses and estimates of the 1 percent AEP or 100-yr recurrence interval flow for comparison to estimates used in the most recent flood studies.

The data used in the preliminary analysis were those available as of March 2009 and the data for the 2009 water year[1] were provisional at that time. Since 2009, flooding of similar magnitude has not occurred in King County. Therefore, this report updates the original analyses of the 2009 flood peaks in the context of the historical flow records using the accepted (i.e., no longer provisional data) published through the 2015 water year.[2] This report also provides updated flood frequency analyses and estimates of the 1 percent AEP or 100-yr recurrence interval flow for comparison to estimates used in the most recent flood studies.

The final published 2009 peak discharge was different than the provisional peak flow analyzed in the initial study at seven gaging stations. Differences between the final and provisional peak discharge values were 4 percent or less, except at the Tolt River near Carnation gage, which changed almost 30 percent. The provisional peak discharge value was 17,900 cfs and the final published value was 13,800 cfs. Regardless, the ranks of the 2009 peak discharges did not change as a result of the changes in the final published peak

[1] A water year is the 12-month period from October 1st through September 30th of the following year. For example, water year 2009 is the period October 1, 2008 through September 30, 2009).
[2] With the exception of data for the USGS station on Newaukum Creek near Black Diamond. The 2015 peak discharge has not been published as of May 25, 2016.

discharge values or as the result of the addition of the published 2010 through 2015 annual peak discharge records.

Record flows were observed at three locations, all within the Snoqualmie River Basin. Near record peak flows (ranked 2nd and 3rd highest) were observed at nine other gaging stations located across the county representing almost every major river basin except the Sammamish. Issaquah Creek in the Sammamish River basin experienced the 4th largest peak flows on record, although Lake Sammamish moderated the effects of these flows such that the peak flow observed in the Sammamish River during the January 2009 storm was ranked 20th.

In general, major flooding events such as the one that occurred in January 2009 are the result of land falling atmospheric rivers. Atmospheric rivers are the water-vapor rich portion of the broader extratropical storms that provide much of the precipitation to mid-latitude coastal areas of the world. There have been a number of recent research studies on the potential effects of climate change on the frequency and/or intensity of extreme precipitation events along the western coast of the United States associated with atmospheric rivers. These studies indicate that precipitation extremes will become more intense and the frequency with which particular thresholds are exceeded will increase (e.g., the number of days with at least 4 in of rain). These factors suggest more frequent and more severe flooding can be expected in the future.

The updated 1 percent AEP discharge (i.e., the 100-yr recurrence interval flood), including upper and lower 95 percent confidence limits are provided in this report. These estimates were compared to those used in previous Flood Insurance Studies (FISs) to help prioritize flood study updates. The comparisons indicated that most differences were relatively small and within the 95 percent confidence intervals of the 1 percent AEP. One notable exception was a relatively large difference for Soos Creek, with the 1 percent AEP from this study being over 40 percent higher than that used in the most recent flood study. This difference is consistent with the observation that urbanization in this basin may have resulted in an increase in annual peak flows since the 1980s when the last FIS was conducted.

Another exception was the 1 percent AEP estimated for the White River above Boise Creek and below Mud Mountain Dam. The 1 percent AEP in this study was 28 percent higher than the most recent preliminary Flood Insurance Study (FIS) estimate, which used an adjusted flow record and assumptions about flow regulation at the dam. The 1 percent AEP estimated in this study is based on a relatively short observational record (13 years) and includes a peak discharge of 14,700 cfs measured in November 2006. Since 2009 the U.S. Army Corps of Engineers has operated with lower annual peak outflows from the project. Thus the estimate from this study is not representative of the current regulated AEP for this location.

A trend toward larger and/or more extreme peak flows, along with potential adaptive changes in reservoir operations, suggests the potential need to address nonstationarity[3] in future flood frequency analyses. However, a recent update to the 17B method (draft Bulletin 17C) does not include procedures that accommodate nonstationarity. Regional flood probability analysis (i.e., the probability of a particular return interval flood occurring anywhere in a region) or the use of weighted independent estimates of flood frequency may also be worth evaluating in future flood frequency studies. At a minimum, it is recommended that the next update of the flood frequency statistics presented in this report evaluate the application of the new Bulletin 17C procedures when they are finalized.

It should also be noted that a study of climate change impacts related to flood sizes and frequencies on the major rivers in King County has recently been funded by the King County Flood Control District. This study began in March 2016 and will be completed at the end of 2017.

[3] The 17B methods assume that the peak discharge time series is stationary, that is it assumes a time-invariant probability density function or more simply that the mean and variance do not change over time.

1.0 INTRODUCTION

Flooding poses significant threats to public health and safety, transportation corridors and economic activities throughout King County. Flooding affects every resident in King County; the County has experienced 12 federally declared flood disasters since 1990, and tens of thousands of county residents commute through, live, and work in floodplains.

Flood hazard assessments in King County (and throughout the United States) are based on analysis of flow data from continuous flow monitoring locations (typically those with at least 10 years of data) or are extrapolated to other locations based on the observed flow records. The flow data analysis is typically performed on records of peak discharge from an annual time series of peak discharges in what is termed a flood frequency analysis. The result of the flood frequency analysis is an estimate of the annual exceedance probability (AEP) of various flow magnitudes. The flood frequency analysis also estimates the *return period* or *recurrence interval*, which are essentially the inverse of the AEP. For example, an annual peak flow with an AEP of 0.01 or 1 percent (i.e., a 1 percent chance of occurring in any given year) is equivalent to a 100-yr recurrence interval flow. Because the flow record is routinely updated as new annual peak flow data are collected, flood frequency estimates can change – especially after an extremely large flood event or for gages with short records.

The focus of this report is to update the flood frequency analyses on rivers with mapped floodplains using data through water year 2015. This assessment slightly revises the findings (reported in King County 2009) of a preliminary assessment of the January 2009 flood event that affected much of western Washington (Mastin et al. 2010). The 2009 King County report was a response to the severity of flooding that occurred and interest in placing that extreme flood event in historical context. This report also provides updated flood frequency analyses and estimates of the 1 percent AEP or 100-yr recurrence interval flow for comparison to estimates used in the most recent flood studies (FEMA, 2013).

The data used by King County (2009) were those available as of March 2009 and the data for the 2009 water year[4] were provisional at that time. Since 2009, flooding of similar magnitude has not occurred in King County. Therefore, this report updates the original analyses of the 2009 flood peaks in the context of the historical flow records using the accepted (i.e., no longer provisional data) published through the 2015 water year.[5]

1.1 Flooding in January 2009

Mastin et al. (2010) provided a summary of the conditions leading up to and including the major flooding that occurred in western Washington in January 2009, which is briefly summarized below.

[4] A water year is the 12-month period from October 1st through September 30th of the following year. For example, water year 2009 is the period October 1, 2008 through September 30, 2009).
[5] With the exception of data for the USGS station on Newaukum Creek near Black Diamond. The 2015 peak discharge has not been published as of July 13, 2016.

Snow was already on the ground even in lowland areas and significant amounts of precipitation were falling in western Washington by January 5, 2009. Heavy rain began to fall by January 6 and continued through January 8, 2009. Air temperatures also rose during this period, resulting in snowmelt runoff, particularly in the lowlands. The weather system was a characteristic "atmospheric river"; an elongate band of warm, moisture laden air originating in the subtropics (Figure 1). Atmospheric rivers are associated with all major flooding in western Washington and are typically strongest from October to March (Neiman et al. 2011).

Although flows at many non-regulated western Washington U.S. Geological Survey (USGS) flow gages set peaks of record, 24-hr precipitation totals measured during the event were not record breaking. Rainfall amounts were similar to an event with a 10-yr recurrence interval (i.e., AEP of 10 percent). Factors that contributed to the severity of the flooding included:

- The effect of prolonged and intense rain resulting in saturated soil conditions that would result in maximum runoff.
- Warm temperatures that resulted in rain rather than snow at higher elevations that generated rainfall runoff rather than storage as snow.
- Warm temperatures and warm rain that resulted in snowmelt contribution to runoff.

When high water conditions are imminent, King County activates its Flood Warning Center. Operation of the center is based on a four-phase warning system, issued independently for each river. Flood phases indicate the severity of flooding and guide King County's response. Flood phases are issued independently for six major river systems (Snoqualmie, Tolt, Issaquah, Cedar, Green and White).

The thresholds for each phase are based on USGS gages which measure the flow and stage (depth) in various river and creek locations. Phase 1 is an internal alert to King County staff. Phase 2 indicates minor flooding in some areas. Phase 3 indicates moderate flooding in some areas. Phase 4 indicates major flooding in areas. During the January 2009 storm event, three of the six river systems reached Phase 4 (Snoqualmie, Tolt and Cedar), while the other three systems reached Phase 3 (Issaquah, Green and White). In addition, the Skykomish River exceeded the National Weather Service flood stage at Gold Bar, Washington (the upstream South Fork Skykomish River drains a large portion of northeastern King County).

1.2 Organization of This Report

The report is organized into an Introduction (Section 1.0), a Methods section (2.0), which includes a description of the flow gaging stations and data selected for analysis, a Results section (3.0) that provides a summary of the results and a final Summary and Conclusions section (4.0) that provides a brief summary and conclusions based on the study results.

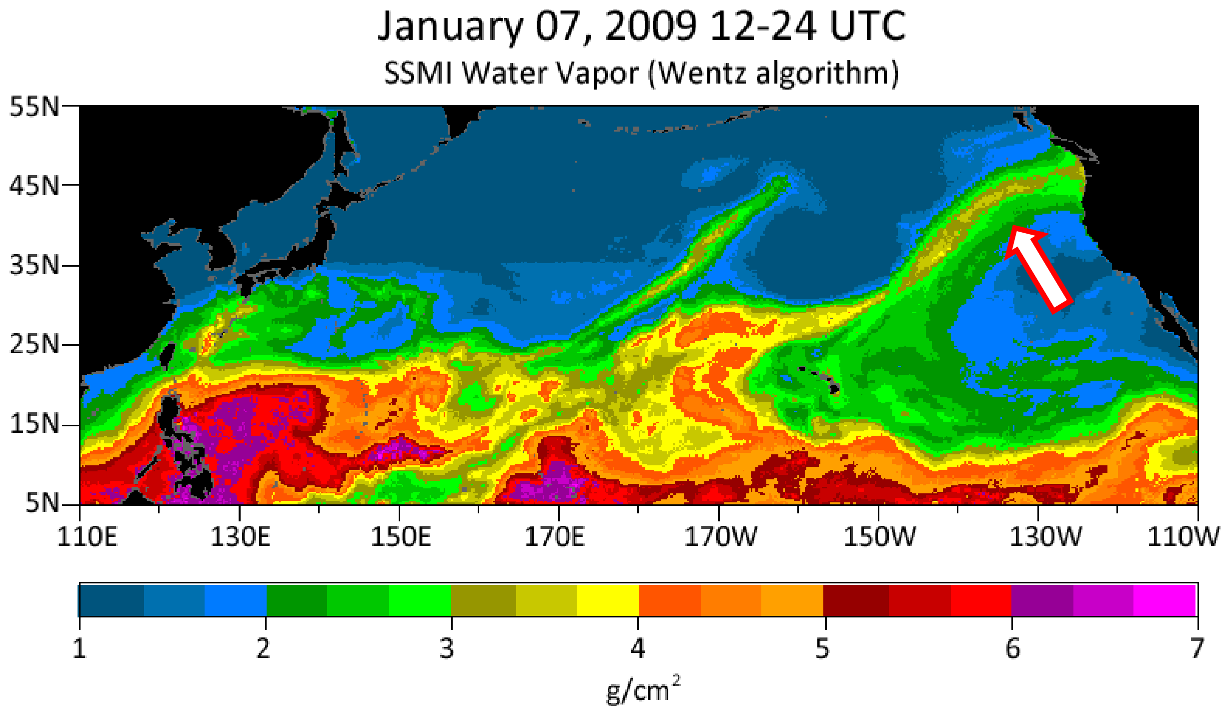

Figure 1. Image from the satellite-based Special Sensor Microwave Imager (SSMI) passive microwave radiometer illustrating the areal water vapor content of the atmosphere on January 7, 2009.

Note: The arrow on the figure points to a high concentration of water vapor (atmospheric river) directed at the Pacific Northwest.

1.3 Study Objectives

The objective of this study was to update the characterization of the effect of a severe January 2009 storm on extreme peak flows in regulated and unregulated stream and river systems draining relatively undeveloped portions of King County using the final published peak flow data available through 2015.[6] The severity of the effect of the storm on peak flow was examined by ranking the annual peak magnitudes (largest to smallest) and by conducting a flow frequency analysis on the systematic record of annual maximum peak flows at selected flow gaging locations.

The flow frequency analysis provided an estimate of the annual exceedance probability of the observed January 2009 event peak flow. The flow frequency analysis also provided updated estimates of the 1 percent AEP or 100-yr recurrence interval flow for comparison to estimates used in the most recent flood studies. Details on the data and analysis methods are provided in the following section.

[6] As noted previously, there was one exception for Newaukum Creek at Black Diamond. The 2015 peak discharge has not been published as of July 13, 2016.

2.0 METHODS

The stations selected for the analyses conducted as part of this report include those selected for preliminary analysis by King County (2009), except for the Snoqualmie River at Duvall, Station 12150400. The Snoqualmie River station at Duvall only reports stage, and although the record extends back to water year 2001, there are many periods of missing data. A number of additional stations were added for this study so that all of the long term USGS gages representing rivers and streams draining to or from primarily undeveloped areas in King County were represented. Data from a total of 25 USGS gages were evaluated (Table 1).[7]

USGS stations with long term records located in highly developed basins were excluded to avoid potential issues of nonstationarity related to urbanization.[8] Data from King County flow gages, with one exception, were not included in this study because the stations in relatively undeveloped areas of the county tend to be on smaller creeks, and systematic annual peak records are not currently maintained and updated on a routine basis. The one exception was the King County gaging station (51T) near Woodinville on the Sammamish River; a former USGS gaging station (12125200) that was taken over by King County in 2006. Therefore, the long term USGS records for that site were extended through 2015 by extracting the annual peak flows from the instantaneous records for Station 51T. The data for this station are identified as USGS gaging station 12125200 in this report.

The flood frequency analysis technique (described in more detail below) assumes that the statistical properties of the peak flow time series are stationary; that is have a time-invariant probability density function or put more simply that the mean and variance do not change over time (Milly et al., 2005). The assumption of stationarity can be compromised by a number of factors related to development, including urbanization, channel modifications, and flow regulation and/or diversion. Natural and human-caused climate changes can also compromise the assumption of stationarity. In the analyses presented in this report, it is assumed that data selected for analysis are reasonably stationary. Steps taken to avoid violations of the assumption of stationarity are described in the explanation of the flood frequency analysis method description below.

The selected stations were further grouped to represent six major river basins that are somewhat different than the river basin groups used as part of the King County Flood Warning System. These basins are as follows:

- Skykomish River – an unregulated river basin that includes drainage from the South Fork Skykomish River in the mountainous northeastern part of King County.

[7] The USGS station on the Sammamish River near Woodinville was operated by the USGS until 2006. The operation of this gauge by King County has continued since then with funding from the King County Flood Control District.

[8] For example, see the annual peak discharge records for Mercer Creek near Bellevue (Station 12120000): http://nwis.waterdata.usgs.gov/nwis/peak?site_no=12120000&agency_cd=USGS&format=img

- Snoqualmie River – a river basin consisting of one regulated tributary (South Fork Tolt) to a tributary (Tolt River) to the unregulated Snoqualmie mainstem and other relatively large unregulated river tributaries above Snoqualmie Falls.
- Sammamish River – a river basin that includes Issaquah Creek, which drains to Lake Sammamish and the Sammamish River, which is the outlet of Lake Sammamish. Lake Sammamish provides some attenuation of flow to the Sammamish River via storage during storms.
- Cedar River – a river basin with upstream regulation as related to the water supply diversion, which also secondarily cause some limited flood flow regulation through the operations at Chester Morse Lake and Masonry Dam.
- Green River – a river basin with upstream regulation that includes a water supply diversion and flood flow regulation through the operation of Howard Hanson Dam.
- White River – a complex river basin that drains a portion of Mt. Rainier and includes a water supply diversion and flood regulation by Mud Mountain Dam.

The size of the individual basins represented by the selected gages varies from 17.6 mi^2 (Issaquah Creek near Hobart) to 1,537 mi^2 (Snohomish River near Monroe) (Table 1). The period of available peak flow records was also variable and ranged from 12 years (White River above Boise Creek at Buckley downstream of Mud Mountain Dam to 116 years (Cedar River near Landsburg below Chester Morse Lake) (Table 1).

For gages that reported annual peak flows prior to regulation, only the period representing regulated flows were used (i.e., starting with 1964 for the Tolt River near Carnation, 1962 for stations on the Green River below Howard Hanson Dam). Significant regulation of the Cedar River began after the completion of Masonry Dam in 1915 for water supply purposes. However, the varying length of records and consideration that operational rules weren't really established until the 1960s, the evaluation of the records for stations on the Cedar River below Chester Morse Lake started in 1964. Time series plots of the annual maximum instantaneous peak flow for the period of record at each streamflow gage is provided in Appendix A.

Visual inspection of the time series plots of annual maximum instantaneous peak flow did not suggest the presence of trends or decadal variability (apart from the obvious influences of the construction of large dams), with one possible exception. The records for Big Soos Creek above the hatchery near the City of Auburn (see Figure A-17) do appear to suggest an increasing trend toward higher annual peak flows since the1960s. This is the most developed of the basins analyzed and has been developing steadily over the years (Konrad and Booth, 2002; WRIA 9 Implementation Technical Committee, 2012).

Although there is some indication of an upward trend in annual maximum daily mean flow in coastal Washington rivers since the 1950s (Mass et al., 2011) and in unregulated King County rivers (King County, 2010), the potential for nonstationarity due to climate change is assumed to be negligible at this time.

As in the preliminary analyses reported by King County (2009), the data for 2009 were included as well as all available data collected between 2010 and 2015. This approach is consistent with the approach that would be taken with any new floodplain mapping or infrastructure design study.

The flood frequency analysis was performed using a Matlab program using the procedures outlined in Bulletin 17B of the Interagency Advisory Committee on Water Data (1982).[9] The procedures described in Bulletin 17B are those that are recommended for flood-frequency analysis by U.S. federal agencies. The bulletin describes procedures for computing flood flow frequency curves based on a series of at least 10 years of annual flood peak data and includes the handling of special cases of zero flows, low outliers, historic peaks, confidence intervals, and expected probabilities for estimated quantiles. The 17B procedures fit a Pearson Type III distribution to the logarithm of the annual peak discharges. The AEP (return interval) of the 2009 peak discharge at each station was then interpolated from the method 17B flood frequency curve.

As noted in King County's (2009) preliminary analysis of the floods of January 2009, fitting a Pearson Type III distribution to data from stations affected by upstream regulation may not be appropriate. Upstream regulation typically results in floods in the middle range of magnitudes to be lower relative to floods that would occur under unregulated conditions. If extreme floods exceed the control capacity of the reservoir, the magnitude of extreme flows would be similar to those of the unregulated flows. This would result in a frequency curve that would have a shape similar to the one presented below (Figure 2), which does not fit a Pearson Type III distribution.

Since peak flows at stations representing unregulated flows are the focus of this study, no other methods were explored for flood frequency analysis at stations with upstream regulation. The analysis of stations with some level of upstream regulation as noted above was confined to the period of regulation (for records that included pre and post-regulation periods) and the results presented do not extrapolate AEPs beyond the limits of the available data. Therefore, the use of methods from Bulletin 17B is considered appropriate for the analyses presented in this report and is consistent with the analyses conducted in the preliminary evaluation of the January 2009 flood event (King County 2009).

As a check on the Matlab implementation of the Bulletin 17B procedures, the official implementation of the method provided by the USGS in the software program PeakFQ (Flynn et al. 2006) was applied to the same records and the results using the two applications were compared. Any inconsistencies in results between the two applications would be identified in the presentation of the results.

[9] Matlab Central Log-Pearson Flood Flow Frequency using USGS 17B: https://www.mathworks.com/matlabcentral/fileexchange/22628-log-pearson-flood-flow-frequency-using-usgs-17b

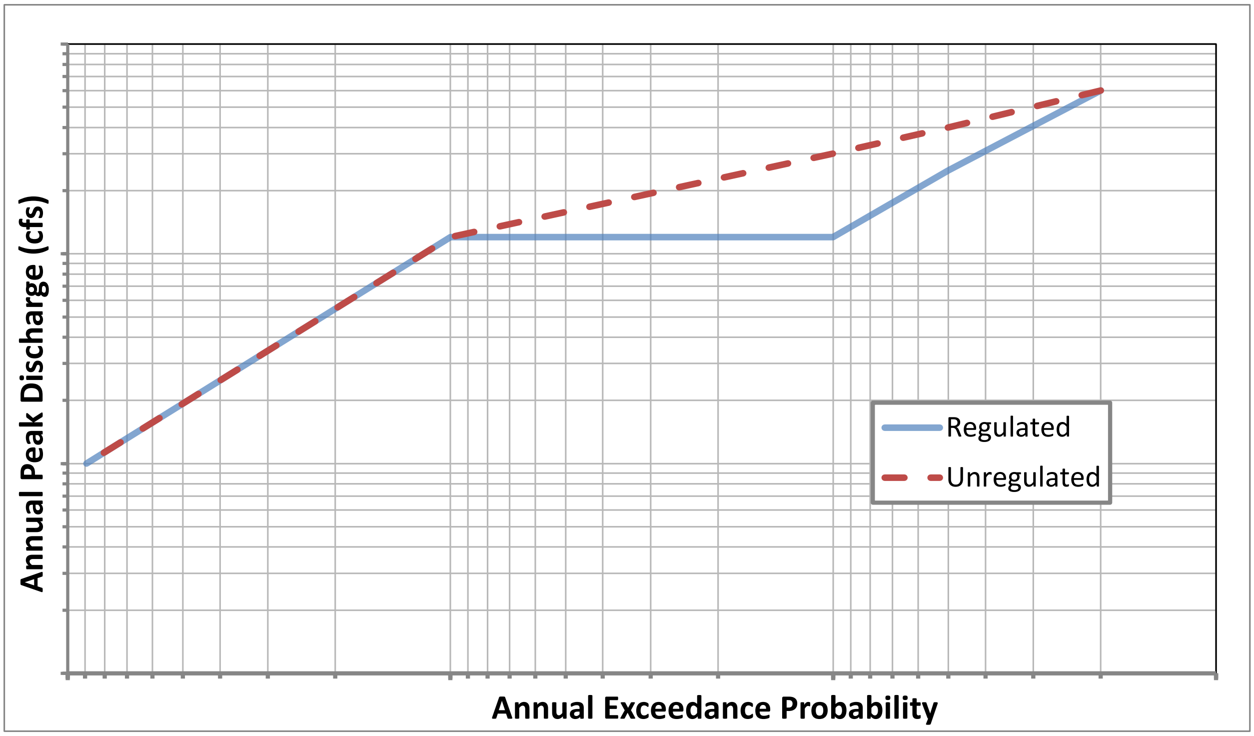

Figure 2. Hypothetical flood frequency curve for a river system with and without regulation.

Note: *Adapted from figure from Bulletin 17-B Guidelines for Determining Flood Frequency Frequently Asked Questions (http://acwi.gov/hydrology/Frequency/B17bFAQ.html).*

Table 1. Summary information for streamflow gaging stations selected for analysis in this study.

Station Name	Site No.	Drainage Area (mi^2)	Period of Record	Number of Annual Peaks in Record	Period of Record Analyzed	Number of Annual Peaks Analyzed
SKYKOMISH RIVER NEAR GOLD BAR	12134500	535	1929-2015	87	1929-2015	87
NF SNOQUALMIE RIVER NEAR SNOQUALMIE FALLS	12142000	64	1930-2015	84	1930-2015	84
MIDDLE FORK SNOQUALMIE RIVER NEAR TANNER	12141300	154	1961-2015	55	1961-2015	55
SF SNOQUALMIE RIVER AB ALICE CREEK NEAR GARCIA	12143400	41.6	1961-2015	55	1961-2015	55
SNOQUALMIE RIVER NEAR SNOQUALMIE	12144500	375	1959-2015	57	1959-2015	57
SNOQUALMIE RIVER NEAR CARNATION	12149000	603	1930-2015	86	1930-2015	86
SNOHOMISH RIVER NEAR MONROE	12150800	1537	1964-2015	52	1964-2015	52
NORTH FORK TOLT RIVER NEAR CARNATION	12147500	39.9	1953-2015	61	1953-2015	61
RAGING RIVER NEAR FALL CITY	12145500	30.6	1946-2015	69	1946-2015	69
SOUTH FORK TOLT RIVER NEAR CARNATION	12148000	19.7	1953-2015	57	1970-2015	46
TOLT RIVER NEAR CARNATION	12148500	81.4	1929-2015	80	1964-2015	52
CEDAR RIVER NEAR CEDAR FALLS	12115000	40.7	1946-2015	67	1946-2015	67
CEDAR RIVER NEAR LANDSBURG	12117500	121	1896-2015	116	1964-2015	52
CEDAR RIVER AT RENTON	12119000	184	1907-2015	70	1964-2015	52
CEDAR RIVER AT CEDAR FALLS	12116500	84.2	1914-2015	101	1964-2015	52
NEWAUKUM CREEK NEAR BLACK DIAMOND	12108500	27.4	1945-2014	70	1945-2014	70
BIG SOOS CREEK ABOVE HATCHERY NEAR AUBURN	12112600	66.7	1961-2015	55	1961-2015	55
GREEN RIVER AT PURIFICATION PLANT NEAR PALMER	12106700	231	1964-2015	52	1964-2015	52
GREEN RIVER NEAR AUBURN	12113000	399	1937-2015	79	1962-2015	54
GREEN RIVER BELOW HOWARD A HANSON DAM	12105900	221	1961-2015	55	1962-2015	54
WHITE RIVER BELOW CLEARWATER RIVER NR BUCKLEY	12097850	375	1975-2015	23	1975-2015	23
WHITE RIVER ABOVE BOISE CREEK AT BUCKLEY	12099200	411	2003-2015	13	2003-2015	13
ISSAQUAH CREEK NEAR MOUTH NEAR ISSAQUAH	12121600	56.6	1964-2015	52	1964-2015	52
ISSAQUAH CREEK NEAR HOBART	12120600	17.6	1986-2015	30	1986-2015	30
SAMMAMISH RIVER NEAR WOODINVILLE	12125200	159	1966-2015	50	1966-2015	50

Note: Grey shading indicates stations considered by the USGS to be regulated by an upstream dam or large lake.

3.0 RESULTS

The results of the flood frequency analyses are summarized in Table 2 and flood-frequency plots for each streamflow gage are provided in Appendix B. The final published 2009 peak discharge was different than the provisional peak flow analyzed in the initial King County (2009) study at seven gaging stations (Table 2). Differences between the final and provisional peak discharge values were 4 percent or less, except at the Tolt River near Carnation gage, which changed almost 30 percent. The provisional peak discharge value was 17,900 cfs and the final published value was 13,800 cfs. Regardless, the ranks of the 2009 peak discharges did not change as a result of the changes in the final published peak discharge values or as the result of the addition of the published 2010 through 2015 annual peak discharge records.

The comparison of the Matlab flow frequency analysis results to those provided by the PeakFQ program identified one significant discrepancy that resulted from a limitation of the Matlab B17.m program; the current version does not recognize qualifier flags. The 1993 peak discharge value published for the Middle Fork Snoqualmie River near Tanner gage is qualified as a "discharge greater than stated value." The PeakFQ program removes this value from the analysis, but the Matlab B17.m program does not. The qualified value was removed from the Matlab input file and the PeakFQ results were reproduced.

The January 2009 storm resulted in record peak flows at 3 of the 25 stations analyzed. All of the record January 2009 peaks were recorded at gages located in the Snoqualmie River basin (North Fork Snoqualmie near Snoqualmie Falls, Tolt River near Carnation, and Snoqualmie River near Carnation). The estimated AEP for the peak flows measured at these gaging stations ranged from 1.3 to 2.5 percent (82 to 41-yr recurrence interval). The period of record for these gaging stations ranged from 40 to 85 years, which should provide a good indication of the range in magnitude of peak flows over the last half century.[10]

Nine other gaging stations recorded the second or third highest peak flow during the January 2009 storm (see Table 2 and Figure 3). These records occurred throughout the county and included stations in the Snoqualmie, Cedar, Green and White River basins. The AEP for the peak flows measured at these stations ranged from 1.3 to 9.8 percent (80 to 10-yr recurrence interval).[11] The only basin where the 2009 peak did not rank within the top three peak flow events on record was the Sammamish River basin, where the flow peaks recorded at the two gages located on Issaquah Creek ranked as the fourth highest (AEP of 8.4 and 12 percent; 12 and 8.1-yr recurrence interval).

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[10] Note that the records for the Tolt River near Carnation extend back to 1929, but annual peaks recorded prior to regulation by the South Fork Tolt Reservoir in 1964 were excluded from the flood frequency analysis.
[11] The AEP of 9.8 percent was estimated for the White River above Boise gauge, which has a relatively short period of record (2003-2015). The next lowest AEP of stations with 2009 peak flows ranked 2-3 is Snoqualmie River near Snoqualmie gauge with an AEP of 5.4 percent (18-yr recurrence interval).

Table 2. Water year 2009 peak flow and annual exceedance probabilities (and return periods) for USGS streamflow gaging stations selected for analysis in this study.

Station Name	Site No.	Period of Record Analyzed	Date of WY 2009 Peak Event	Peak Flow Final (Prov.)[a]		Rank in Record	AEP (%)	Return Period (yr)	95 percent confidence limits	
									Upper	Lower
SKYKOMISH RIVER NEAR GOLD BAR	12134500	1929-2015	1/8/2009	74,000		12	11	9	84,240	66,630
NF SNOQUALMIE RIVER NEAR SNOQUALMIE FALLS	12142000	1930-2015	1/7/2009	17,100		1	1.8	55	19,790	15,180
MIDDLE FORK SNOQUALMIE RIVER NEAR TANNER	12141300	1961-2015	1/7/2009	31,200		2	4.3	23	36,640	27,470
SF SNOQUALMIE RIVER AB ALICE CREEK NEAR GARCIA	12143400	1961-2015	1/7/2009	7,440		5	7.9	13	8,936	6,482
SNOQUALMIE RIVER NEAR SNOQUALMIE	12144500	1959-2015	1/7/2009	60,700		3	5.4	18	71,530	52,820
SNOQUALMIE RIVER NEAR CARNATION	12149000	1930-2015	1/8/2009	82,900	(83,400)	1	1.3	80	98,280	72,410
SNOHOMISH RIVER NEAR MONROE	12150800	1964-2015	1/8/2009	132,000	NA	3	2.1	48	157,100	116,000
NORTH FORK TOLT RIVER NEAR CARNATION	12147500	1953-2015	1/7/2009	9,140	(9,180)	2	4.1	25	10,580	8,173
RAGING RIVER NEAR FALL CITY	12145500	1946-2015	1/7/2009	3,490	(3,410)	8	10	9.6	4,041	3,152
SOUTH FORK TOLT RIVER NEAR CARNATION	12148000	1970-2015	1/8/2009	3,970		2	1.3	75	5,905	2,943
TOLT RIVER NEAR CARNATION	12148500	1964-2015	1/8/2009	13,800	(17,900)	1	2.5	40	16,910	11,790
CEDAR RIVER NEAR CEDAR FALLS	12115000	1946-2015	1/7/2009	6,640	NA	4	4.7	21	7,978	5,700
CEDAR RIVER NEAR LANDSBURG	12117500	1964-2015	1/8/2009	7,870		3	2.4	41	10,140	6,504
CEDAR RIVER AT RENTON	12119000	1964-2015	1/8/2009	9,390	(9,400)	2	2.3	43	12,030	7,763
CEDAR RIVER AT CEDAR FALLS	12116500	1964-2015	1/8/2009	5,330	NA	5	3.9	26	6,999	4,344
NEWAUKUM CREEK NEAR BLACK DIAMOND	12108500	1945-2014	1/8/2009	1,120	NA	12	13	7.6	1,325	1,007
BIG SOOS CREEK ABOVE HATCHERY NEAR AUBURN	12112600	1961-2015	1/8/2009	1,860	NA	2	3.8	26	2,322	1,559
GREEN RIVER AT PURIFICATION PLANT NEAR PALMER	12106700	1964-2015	1/14/2009	8,370	(8,050	21	35	2.8	9,013	7,758
GREEN RIVER NEAR AUBURN	12113000	1962-2015	1/9/2009	11,100		8	17	5.9	12,230	10,290
GREEN RIVER BELOW HOWARD A HANSON DAM	12105900	1962-2015	1/13/2009	8,080	NA	22	38	2.7	8,795	7,543
WHITE RIVER BELOW CLEARWATER RIVER NR BUCKLEY	12097850	1975-2015	11/12/2008	18,100	NA	7	21	4.7	24,430	14,370
WHITE RIVER ABOVE BOISE CREEK AT BUCKLEY	12099200	2003-2015	1/8/2009	11,800	(11,400)	2	9.8	10	16,420	9,565
ISSAQUAH CREEK NEAR MOUTH NEAR ISSAQUAH	12121600	1964-2015	1/8/2009	2,450		4	12	8.1	2,892	2,130
ISSAQUAH CREEK NEAR HOBART	12120600	1986-2015	1/7/2009	1,290		4	8.4	12	1,708	1,047
SAMMAMISH RIVER NEAR WOODINVILLE	12125200	1966-2015	1/8/2009	1,540		20	38	2.6	1,668	1,427

[a] Provisional 2009 peak streamflow values that were different from the final published values shown in parentheses. NA indicates stations that were not analyzed in King County (2009).

Note: Grey shading indicate stations considered by the USGS to be regulated by an upstream dam or large lake.

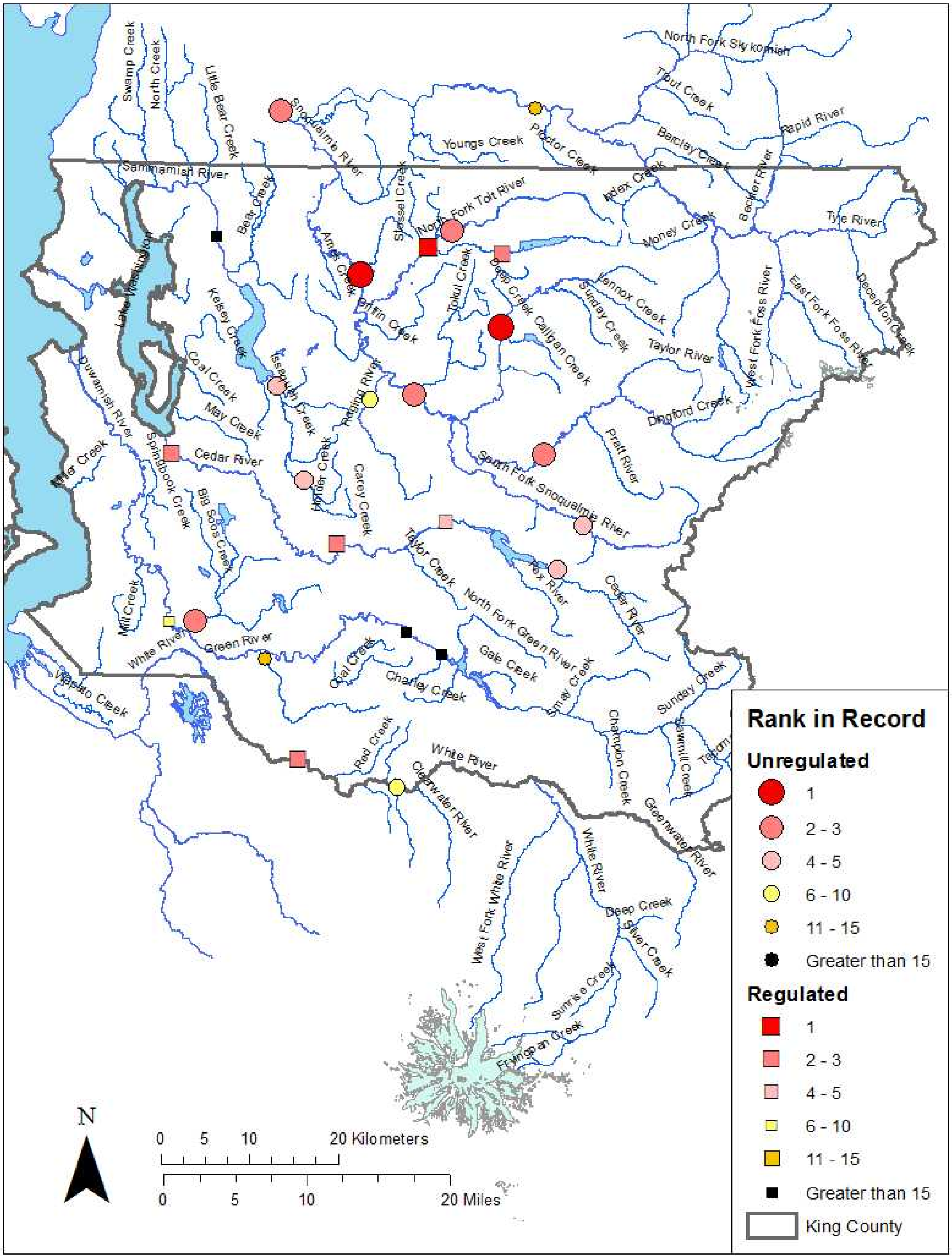

Figure 3. Rank of January 2009 peak discharge on regulated and unregulated streams and rivers draining relatively undeveloped areas of King County for the period of record at U.S. Geological Survey streamflow-gaging stations with 10 or more years of data.

Note: See Table 2 for details of the period of record analyzed for each gage.

2009 flow peaks ranking in the top three events occurred on regulated and unregulated creeks and rivers, which is due in part to the influence of unregulated tributary inflows on regulated river systems. For example, the Tolt River near Carnation experienced the highest peak flow since regulation began in 1964, due predominantly to inflows from the unregulated North Fork Tolt and other tributaries below the South Fork Tolt Reservoir. This is in contrast to the three stations on the Green River below Howard Hanson Dam, which experienced peak flows that ranked between 8th and 22nd over the period since regulation began in 1962. This in spite of the influence of unregulated tributary inflows below the dam as suggested by the rank of the January 2009 peak observed at Big Soos Creek near Auburn, which ranked second over about the same period of record. The strong regulatory effect of flood storage in Lake Sammamish on peak flow in the Sammamish River was also evident as the rank of the January 2009 event was 20th compared to the major lake tributary Issaquah Creek, which ranked 4th over a similar period of record.

The influence and complications of tributaries, regulation, storm tracks, and a limited systematic peak record can be seen by looking at the water year 2009 peak annual flows at the two locations on the White River. Above Mud Mountain Dam in the unregulated portion of the White River (below the Clearwater River near Buckley), the annual peak flow was ranked 7th overall (for the period of record 1975-2015). However, the water year 2009 peak flow at that station was observed almost two months earlier (12 November 2008) than the other stations evaluated in this study. Below the dam at the station above the confluence with Boise Creek, the water year 2009 peak flow ranked 2nd , after the 2006 peak flow, but the period of record is relatively short at that station (2003-2015). Without a more thorough analysis it is not possible to determine what role reservoir operations, storm track, upstream tributary inputs, or record length played in ranking the 2009 peak flow at White River above Boise Creek station 2nd highest on record. It should be noted that this statistical analysis does not capture the complex history of flooding and flooding impacts on the White river due to ongoing sediment deposition, historical sediment management, changing water diversion practices, and changing flood flow regulation practices at MMD. These complexities occurred both before and during the limited systematic peak records available for the White River used in this study.

The updated 1 percent AEP discharge (i.e., the 100-yr recurrence interval flood), including upper and lower 95 percent confidence limits are presented in Table 3. These estimates are compared to those used in the preliminary Flood Insurance Study (FIS) to help prioritize flood study updates.

In cases where the King County FIS reference point is the same or reasonably close to the USGS gaging station, differences between the 1 percent AEP (100-yr return period) from this study and the one used in the most recent FIS were relatively small and were within the 95 percent confidence limits of this study (Table 3). The few preliminary FIS flows that were not within the 95 percent confidence interval of this study were lower than the 1 percent AEP estimates in this study (Big Soos Creek, two stations on the Green River below Howard Hanson Dam, and one station on the White River below Mud Mountain Dam).

The relative difference of the 1 percent AEP for the Soos Creek gaging station was relatively large (the FIS flow was about 40 percent lower than in this study). This difference is consistent with the suggestion that basin urbanization is resulting in an increasing trend in annual peak flow magnitudes. The most recent Soos Creek FIS was based on 26 years of USGS annual peak flow data (1961-1986) with a maximum annual peak flow of 1,090 cfs. However, since 1986, annual peak flows higher than this have been observed five times with a maximum annual peak of 4,200 cfs observed in February 1996 (see Figure A-17 in Appendix A).

The 1 percent AEP estimated in this study for the White River above Boise Creek (downstream of Mud Mountain Dam) was about 28 percent higher than the estimate in the most recent preliminary FIS. This is due in part to the way the 1 percent AEP was estimated in this study compared to the methodology used in the FIS. In the most recent FIS, the estimate of the annual peak discharge quantiles (including the 1 percent AEP) for the area below the dam and just below the confluence with Boise Creek was based on a frequency analysis of an adjusted Mud Mountain Dam discharge record that assumed that the discharges up to and including the 100-yr event would be controlled to 12,000 cfs when feasible per the dam's Water Control Manual (WCM).[12] Since the 2009 event the U.S. Army Corps of Engineers has had a Deviation to the WCM in place that allows them to operate with lower flows – 8,000 cfs and less. The 1 percent AEP estimated in this study is based on a relatively short observational record (13 years), includes a peak discharge of 14,700 cfs measured in November 2006, and includes six years of operating under a deviation to the WCM. Maintaining a reliable long term flow gage on the White River has proved difficult; there is no current long term gaging station record with which to conduct a reliable flow frequency analysis. The longest historic record for the White River was at the USGS station, White River near Buckley, WA 12098500 from 5/24/1929 through 1/18/2005. The differences in the 1 percent AEP estimates for the White River illustrate another source of nonstationarity (i.e., changes in reservoir operations) can be problematic for flood frequency analyses; particularly when combined with limited systematic peak flow records.[12]

The only other relatively large differences noted were cases where the most upstream FIS location was still downstream of the representative USGS gaging station. In those cases the FIS 1 percent AEP was higher than the estimate from this study.
The comparisons for the two Snohomish County FISs indicated a small (4 percent) difference for the Skykomish River and a relatively large difference (37 percent) for the Snohomish River near Monroe. The 1 percent AEP for the Snohomish River FIS was relatively higher than the estimate from this study.

[12] Letter from Larry Karpack (northwest hydraulic consultants) to Jeanne Stypula (King County WLR Division, Rivers Section) RE: White River Hydrology Recommendation, April 24, 2008.

Table 3. **Updated 1 percent annual exceedance probability (AEP) discharge (100-yr recurrence interval) for USGS streamflow gaging stations selected for analysis in this study, including upper and lower 95 percent confidence limits. Where available, the 1 percent AEP discharge used in the latest Flood Insurance Study (FIS) is provided for comparison.**

			Annual 1 % Exceedance Probability Discharge			
		Period of Record	Bulletin 17B	Confidence Limits		Latest FIS
Station Name	**Site No.**	**Analyzed**	**Estimate**	**Upper**	**Lower**	**Estimate [a]**
Skykomish River near Gold Bar	12134500	1929-2015	123,500	148,600	106,400	128,000 [b]
NF Snoqualmie River near Snoqualmie Falls	12142000	1930-2015	18,590	21,740	16,380	21,700
MF Snoqualmie River near Tanner	12141300	1961-2015	37,570	45,420	32,470	38,600
SF Snoqualmie above Alice Creek	12143400	1961-2015	10,900	13,800	9,100	14,900 [c]
Snoqualmie River near Snoqualmie	12144500	1959-2015	80,710	99,870	68,510	79,100
Snoqualmie River near Carnation	12149000	1930-2015	85,980	102,300	74,760	91,800
Snohomish River near Monroe	12150800	1964-2015	148,200	179,500	128,300	196,800 [d]
NF Tolt near Carnation	12147500	1953-2015	11,310	13,480	9,873	- [e]
Raging River near Fall City	12145500	1946-2015	5,832	7,149	4,973	6,970
SF Tolt near Carnation	12148000	1970-2015	4,298	6,508	3,161	- [e]
Tolt River near Carnation	12148500	1964-2015	16,090	20,240	13,520	18,800
Cedar River near Cedar Falls	12115000	1946-2015	9,096	11,430	7,595	-
Cedar River near Landsburg	12117500	1964-2015	10,170	13,680	8,148	10,300
Cedar River at Renton	12119000	1964-2015	11,540	15,330	9,321	12,000
Cedar River at Cedar Falls	12116500	1964-2015	8,544	12,130	6,578	- [e]
Newaukum Creek near Black Diamond	12108500	1945-2014	2,354	3,010	1,943	- [e]
Big Soos Creek above hatchery	12112600	1961-2015	2,693	3,584	2,170	1,550
Green River at Purification Plant near Palmer	12106700	1964-2015	13,630	15,740	12,210	12,070
Green River near Auburn	12113000	1962-2015	14,750	16,860	13,300	12,810
Green River below Howard Hanson	12105900	1962-2015	13,060	15,030	11,720	12,070
White River below Clearwater	12097850	1975-2015	43,250	72,960	30,760	- [e]
White River above Boise Creek	12099200	2003-2015	18,120	30,580	13,640	13,000
Issaquah Creek near Issaquah	12121600	1964-2015	3,846	4,876	3,208	3,560
Issaquah Creek near Hobart	12120600	1986-2015	2,087	3,089	1,593	3,360 [f]
Sammamish River near Woodinville	12125200	1966-2015	2,818	3,316	2,492	2,590

[a] The annual 1 percent AEP discharge values are from King County Flood Insurance Studies, except where noted.
[b] From the Snohomish County FIS for the Skykomish River.
[c] Most upstream value in FIS representing drainage from a 66 mi^2 area. Gaging site upstream represents a 41.5 mi^2 drainage area.
[d] From the Snohomish County FIS for the Snohomish River.
[e] No FIS study has been conducted for this river reach.
[f] Most upstream value in FIS representing drainage from 40 mi^2 area. Gaging site upstream represents a 17.6 mi^2 drainage area.

4.0 SUMMARY

This study evaluated annual peak flow data recorded at stations representing regulated and unregulated stream and river systems draining relatively undeveloped areas of King County. The objective of the study was to characterize the severity of high flows resulting from the large storm that affected all of western Washington in January 2009 and to update the 1 percent AEP (100-yr return period) discharge for comparison to estimates used in the most recent flood studies.

Record flows were observed during the 2009 flood event at three locations, all within the Snoqualmie River Basin. Near record peak flows (ranked 2nd and 3rd highest) were observed at nine other gaging stations located across the county representing almost every major river basin except the Sammamish. Issaquah Creek in the Sammamish River basin experienced the 4th largest peak flows on record, although Lake Sammamish moderated the effects of these flows. The peak flow observed in the Sammamish River during the January 2009 storm was ranked 20th.

The comparison of the 1 percent AEP calculated in this study to the estimates in the most recent flood studies indicated that most differences were relatively small and within the 95 percent confidence intervals of the 1 percent AEP. One notable exception was a relatively large difference for Soos Creek, with the 1 percent AEP from this study being over 40 percent higher than that used in the most recent flood study. This difference is consistent with the observation that urbanization in this basin may be causing an increasing trend in annual peak flow magnitudes over time.

In general, major flooding events such as the one that occurred in January 2009 are the result of land falling atmospheric rivers (Neiman et al 2011). Coincidentally, Neiman et al. (2011) analyzed peak annual daily mean flow data representing inflow to Howard Hanson Dam on the Green River for the period 1980-2009 and determined that the January 2009 peak was the highest observed over this period. The January 2009 event also resulted in the highest recorded pool elevation behind Howard Hanson Dam.

Neiman et al. (2011) showed that the potential impact of an atmospheric river event on any given river basin, particularly the Green River, is mediated by rain shadowing and basin orientation. In particular, they noted the relatively large variability of annual maximum daily mean flows above Howard Hanson Dam on the Green River due to the narrow range of low-level, onshore wind directions that can reach the basin unobstructed by the complex terrain.

This study used annual maximum instantaneous peak flow data through 2015 to assess the relative severity of the January 2009 storm event. It might be useful to conduct a similar analysis using peak annual daily mean flow data as in Neiman et al. (2011) to provide more information on the total volume of an event, which may be as relevant as instantaneous peak flow to flood-risk management. This approach would also allow for the use of the estimated daily mean inflow to Howard Hanson Dam to be included in the analysis.

There have been a number of recent research studies on the potential effects of climate change on the frequency and/or intensity of extreme precipitation events along the western coast of the United States associated with atmospheric rivers (e.g., Dettinger, 2011; Gao et al., 2015; Warner et al., 2015; Hagos et al., 2016). These studies indicate that precipitation extremes will become more intense. This is because the primary driver of changing precipitation intensity is the increase in moisture convergence during these events. Since the heaviest events are projected to become more intense, there will also be an increase in the frequency with which extreme thresholds are exceeded (e.g., the number of days with at least 4 in of rain).

A trend toward larger and/or more extreme peak flows, along with potential adaptive changes in reservoir operations, suggests the potential need to address nonstationarity in future flood frequency analyses (Milly et al., 2005). However, a recent update to the 17B method (draft Bulletin 17C; England et al., 2015), does not include procedures that accommodate nonstationarity. Regional flood probability analysis (i.e., the probability of a particular return interval flood occurring anywhere in a region) (e.g., Troutman and Karlinger, 2003) or the use of weighted independent estimates of flood frequency (e.g., Mastin et al., 2010) may also be worth evaluating in future flood frequency studies. At a minimum, it is recommended that the next update of the flood frequency statistics presented in this report evaluate the application of the new Bulletin 17C procedures. These procedures are available in the version of PeakFQ used in this study.

It should also be noted that a study of climate change impacts related to flood sizes and frequencies on the major rivers in King County has recently been funded by the King County Flood Control District. This study began in March 2016 and will be completed at the end of 2017.

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Appendix A: Annual Maximum Flow Time Series Plots

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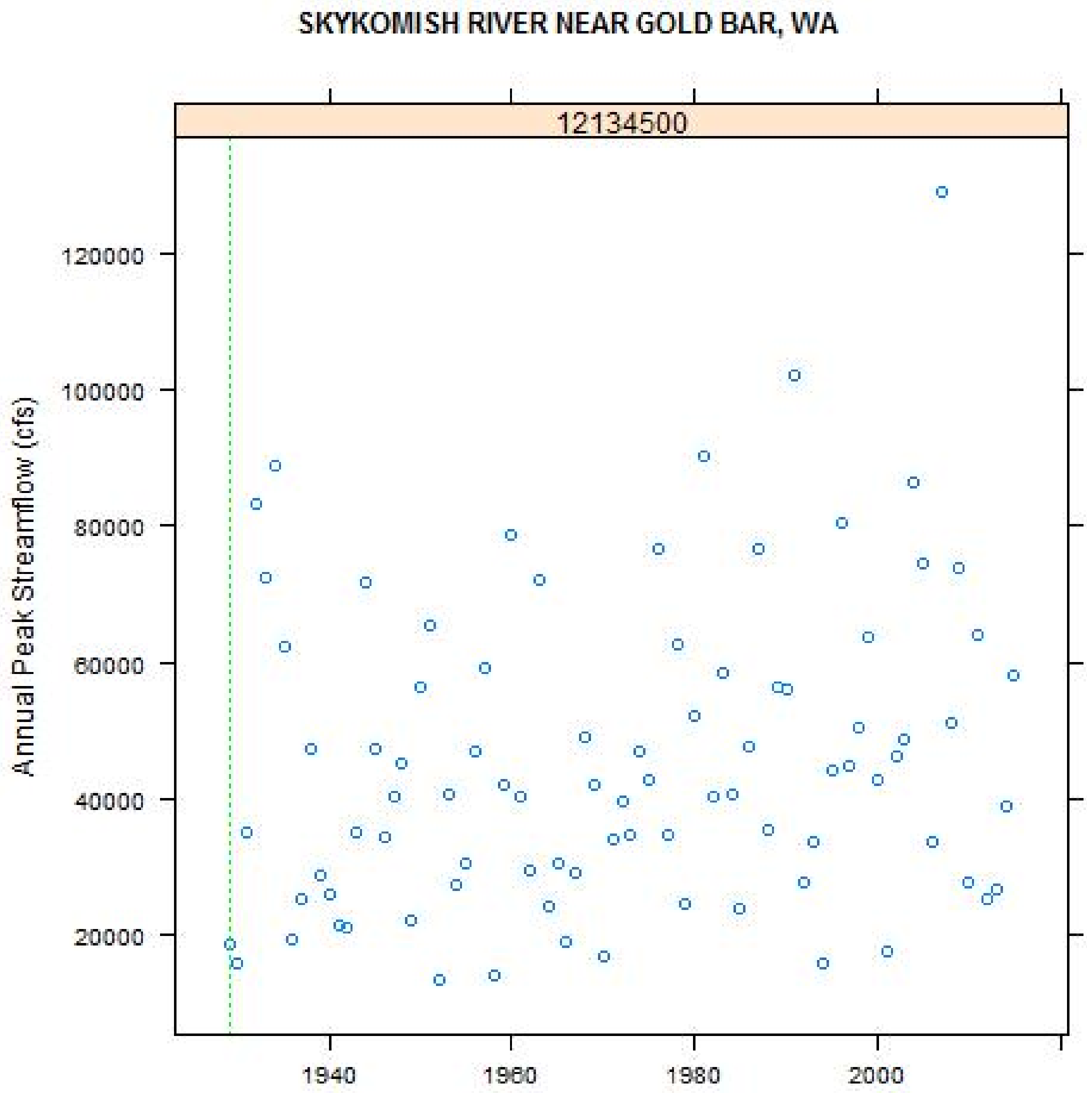

Figure A-1. Time series plot of annual instantaneous peak flow for the Skykomish River near Gold Bar stream gaging station 12134500 (Note: Vertical green line indicates the start year of analysis).

REMARKS - No regulation. Several small diversions upstream from station.

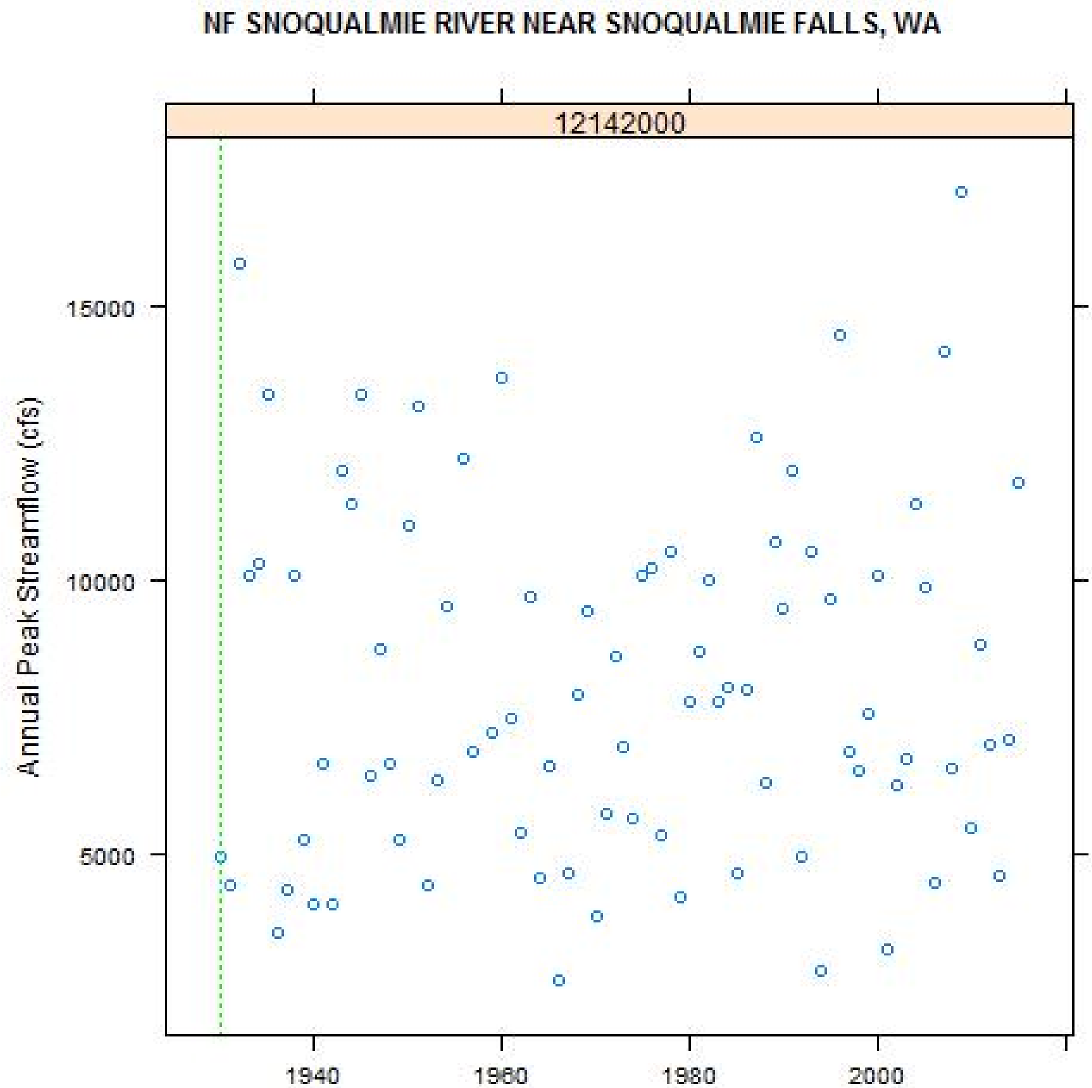

Figure A-2. Time series plot of annual instantaneous peak flow for the North Fork Snoqualmie River near Snoqualmie Falls stream gaging station 12142000 (Note: Vertical green line indicates the start year of analysis).

REMARKS - No regulation or diversion upstream from station.

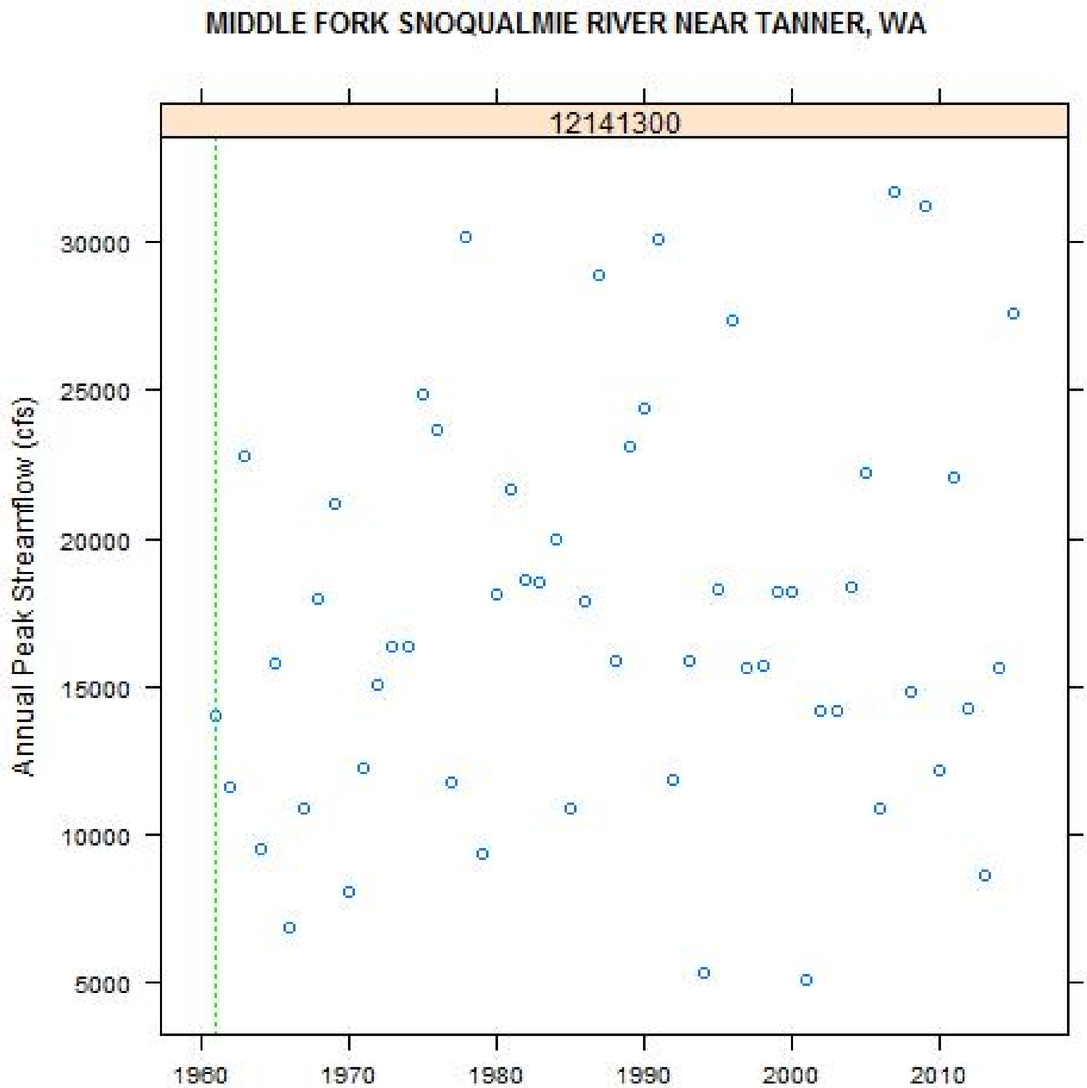

Figure A-3. Time series plot of annual instantaneous peak flow for the Middle Fork Snoqualmie River near Tanner stream gaging station 12141300 (Note: Vertical green line indicates the start year of analysis).

REMARKS - No regulation or diversion upstream from station.

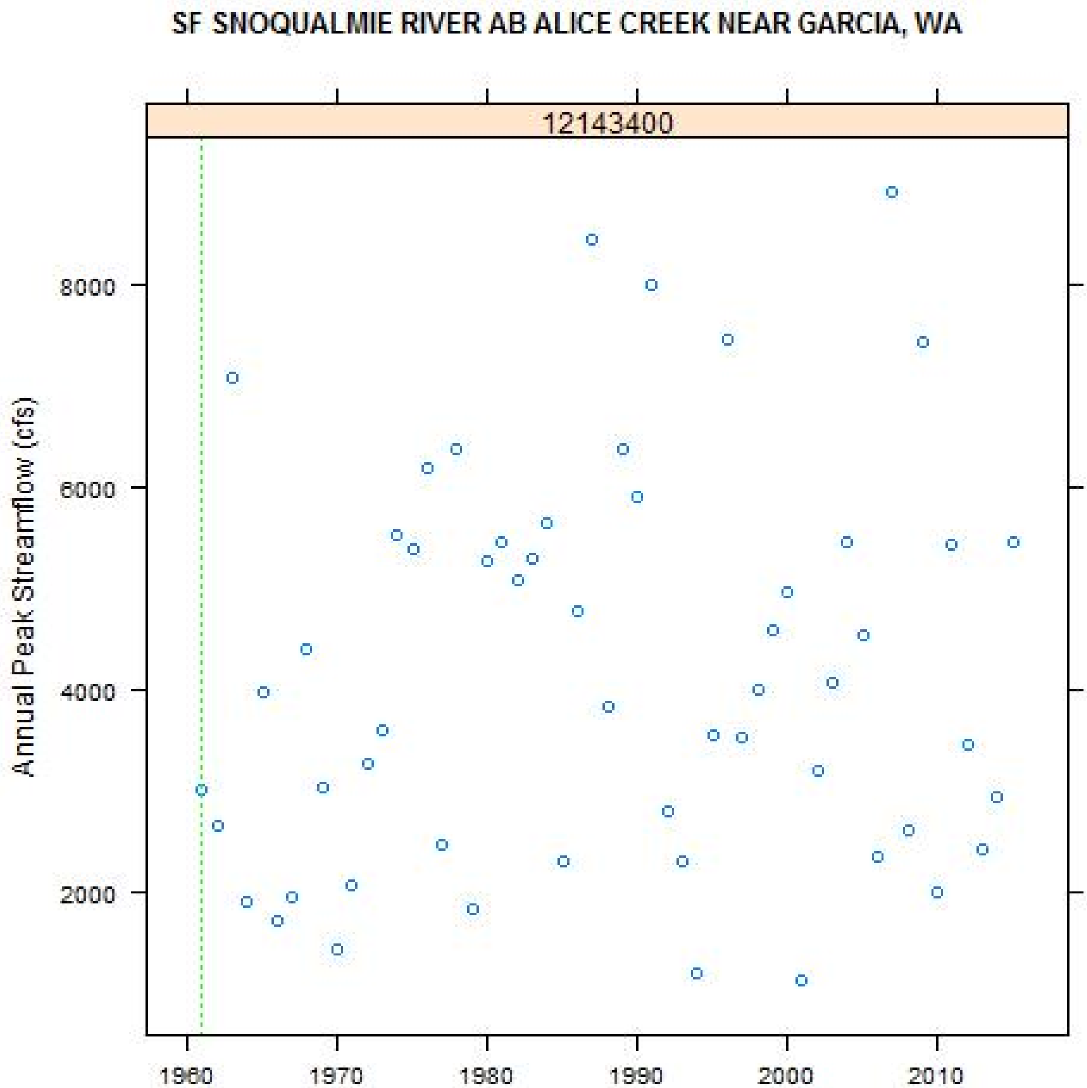

Figure A-4. Time series plot of annual instantaneous peak flow for the South Fork Snoqualmie above Alice Creek stream gaging station 12143400 (Note: Vertical green line indicates the start year of analysis).

REMARKS - No regulation or diversion upstream from station.

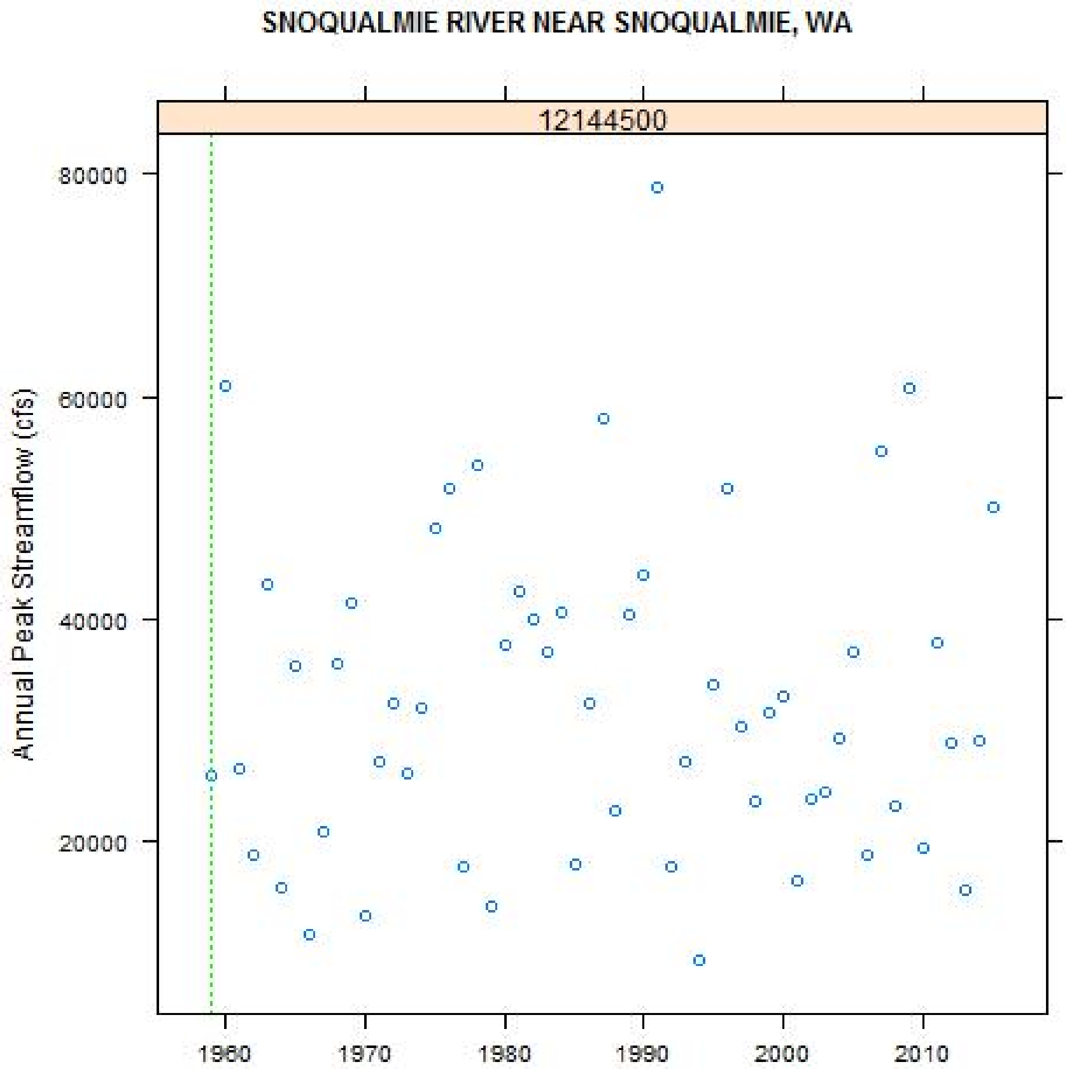

Figure A-5. Time series plot of annual instantaneous peak flow for the Snoqualmie River near Snoqualmie stream gaging station 12144500 (Note: Vertical green line indicates the start year of analysis).

REMARKS - Medium and low flows affected by powerplant 0.1 mi upstream from station. Considered unregulated in the analyses presented in this report.

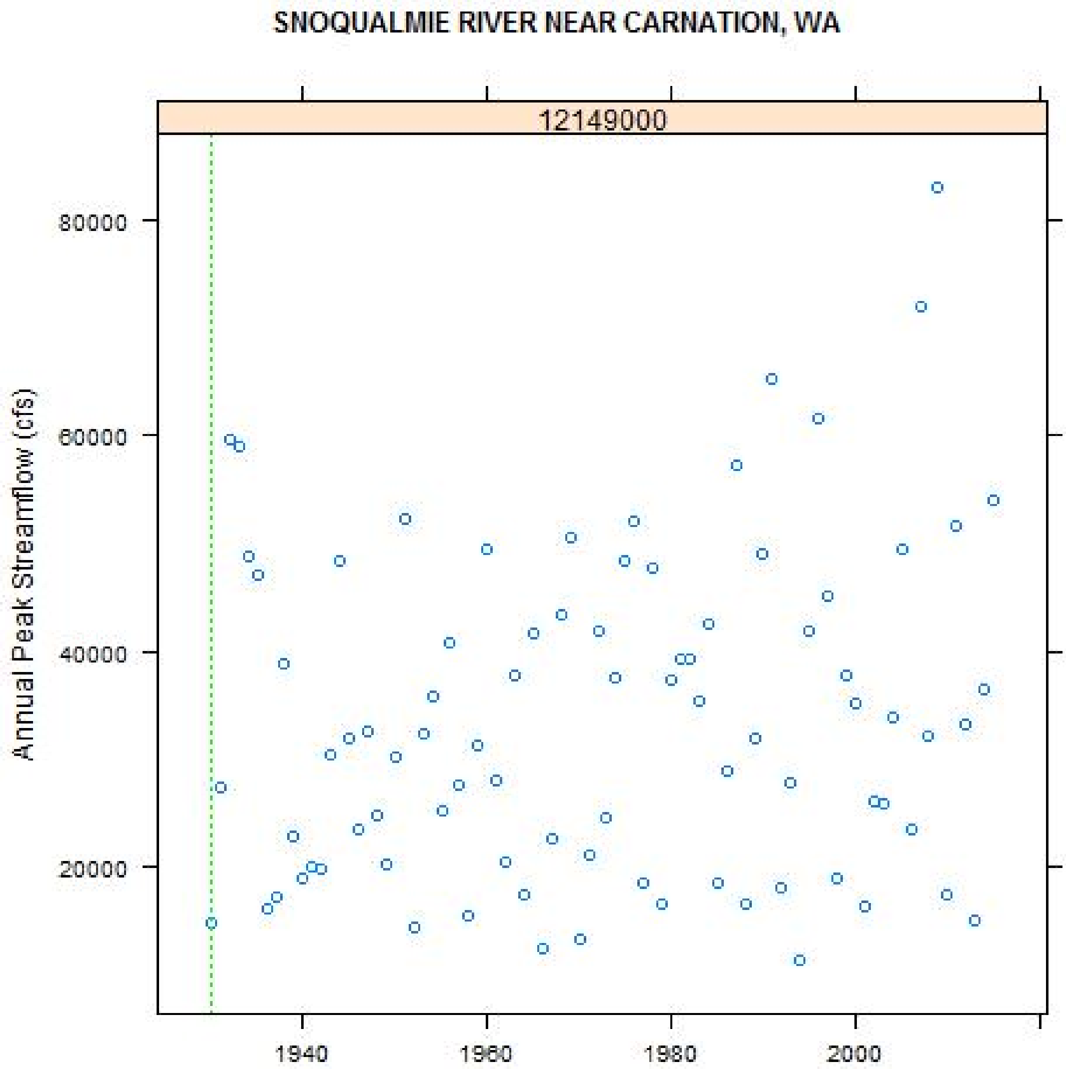

Figure A-6. Time series plot of annual instantaneous peak flow for the Snoqualmie River near Carnation stream gaging station 12149000 (Note: Vertical green line indicates the start year of analysis).

REMARKS - Seattle Water Department diverts water upstream from station from South Fork Tolt River for municipal use. Several small diversions for irrigation and domestic use upstream from station. Some pondage at Snoqualmie Falls and some diurnal fluctuation caused by powerplant.

Considered unregulated in the analyses presented in this report.

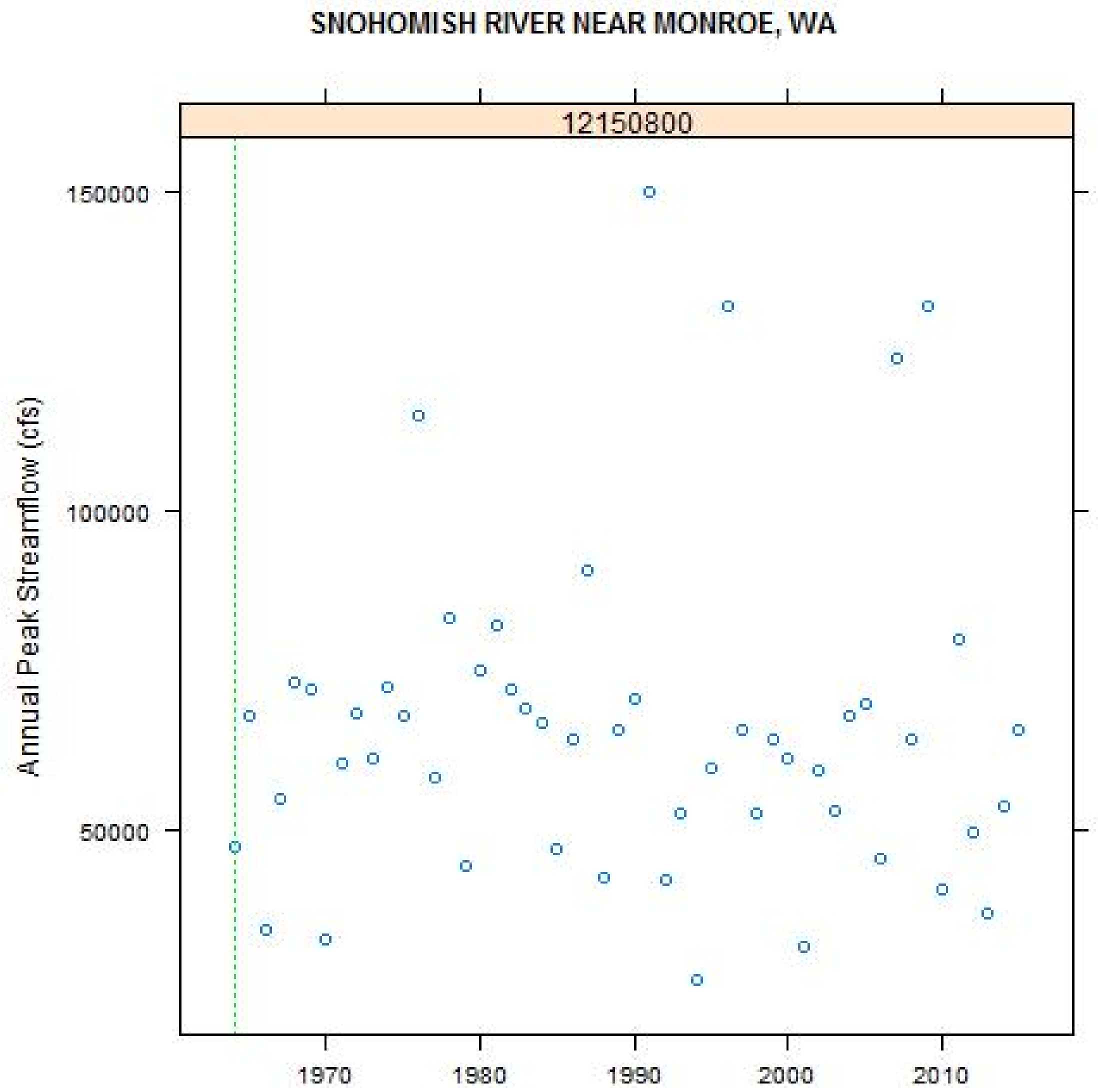

Figure A-7. Time series plot of annual instantaneous peak flow for the Snohomish River near Monroe stream gaging station 12150800 (Note: Vertical green line indicates the start year of analysis).

REMARKS - Some regulation by powerplant at Snoqualmie Falls, 40 mi upstream, and by Spada Lake, 30 mi upstream. Minor diversions for irrigation returned to river upstream from gage. Seattle Water Department diverts water upstream from station from South Fork Tolt River for municipal use and the City of Everett diverts water upstream from the station from Sultan River for municipal use.

Considered unregulated in the analyses presented in this report.

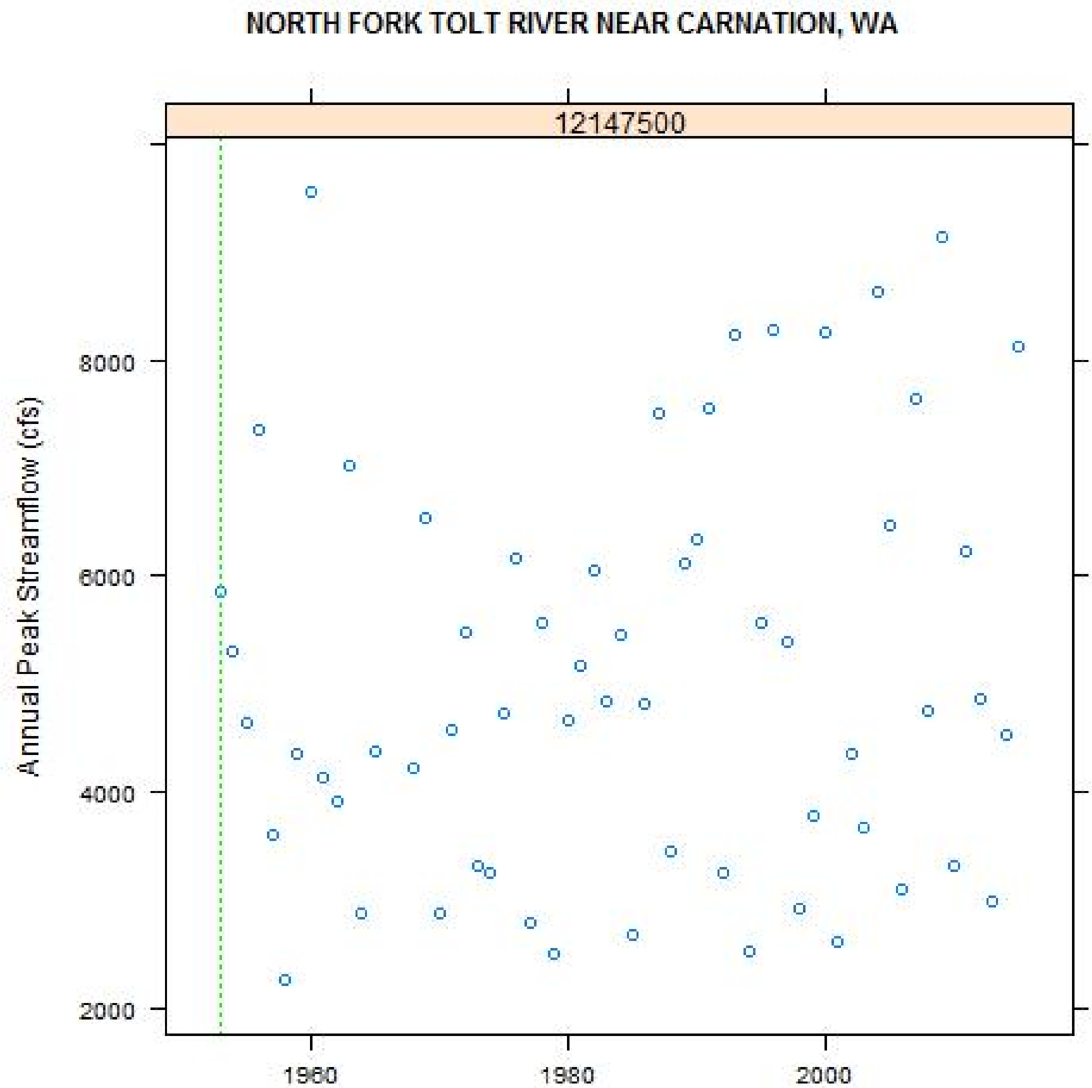

Figure A-8. Time series plot of annual instantaneous peak flow for the North Fork Tolt near Carnation stream gaging station 12147500 (Note: Vertical green line indicates the start year of analysis).

REMARKS - No regulation or diversion upstream from station.

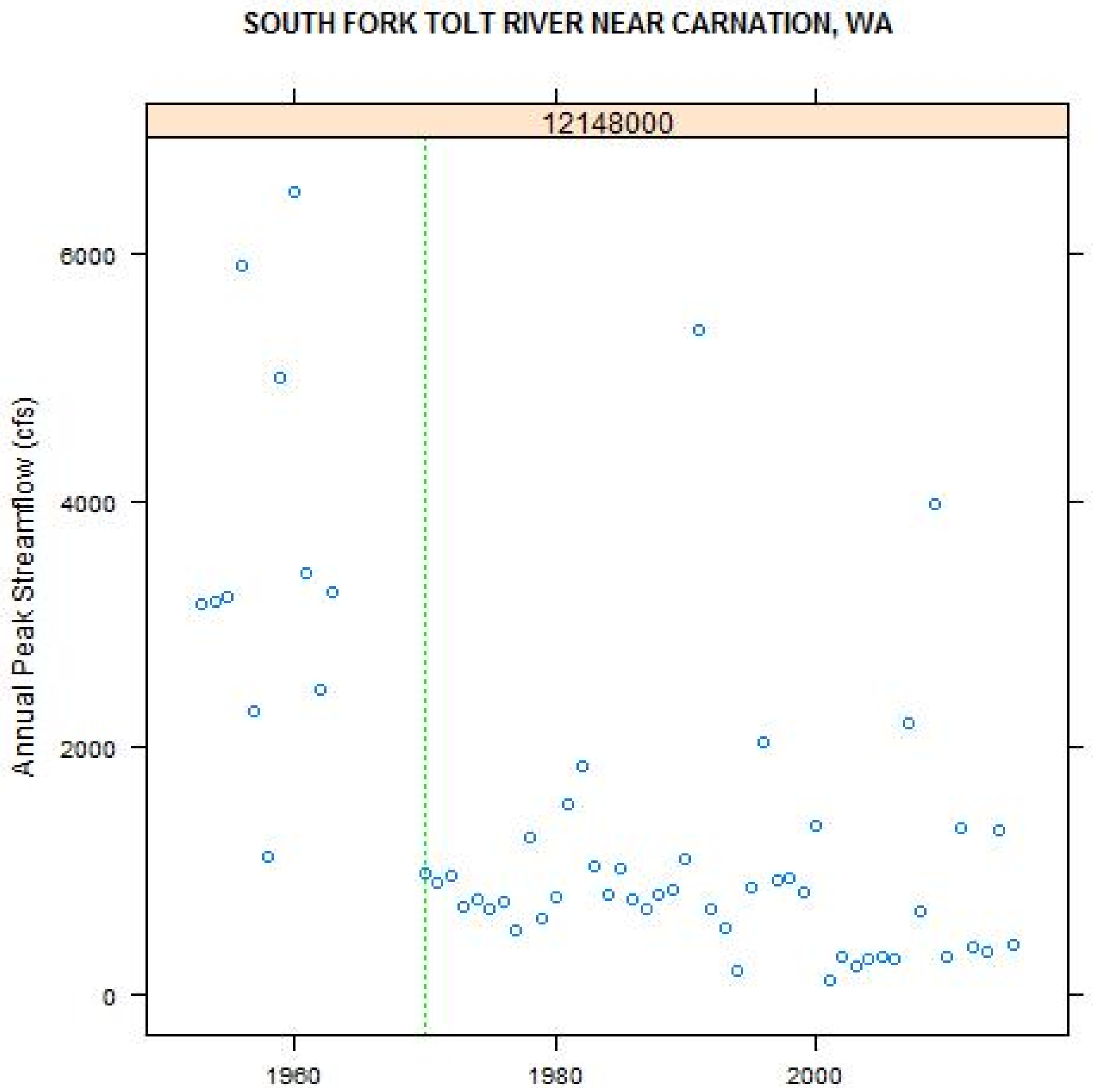

Figure A-9. Time series plot of annual instantaneous peak flow for the South Fork Tolt near Carnation stream gaging station 12148000 (Note: Vertical green line indicates the start year of analysis).

REMARKS - Regulation by South Fork Tolt Reservoir since September 1963.

Considered regulated in the analyses presented in this report.

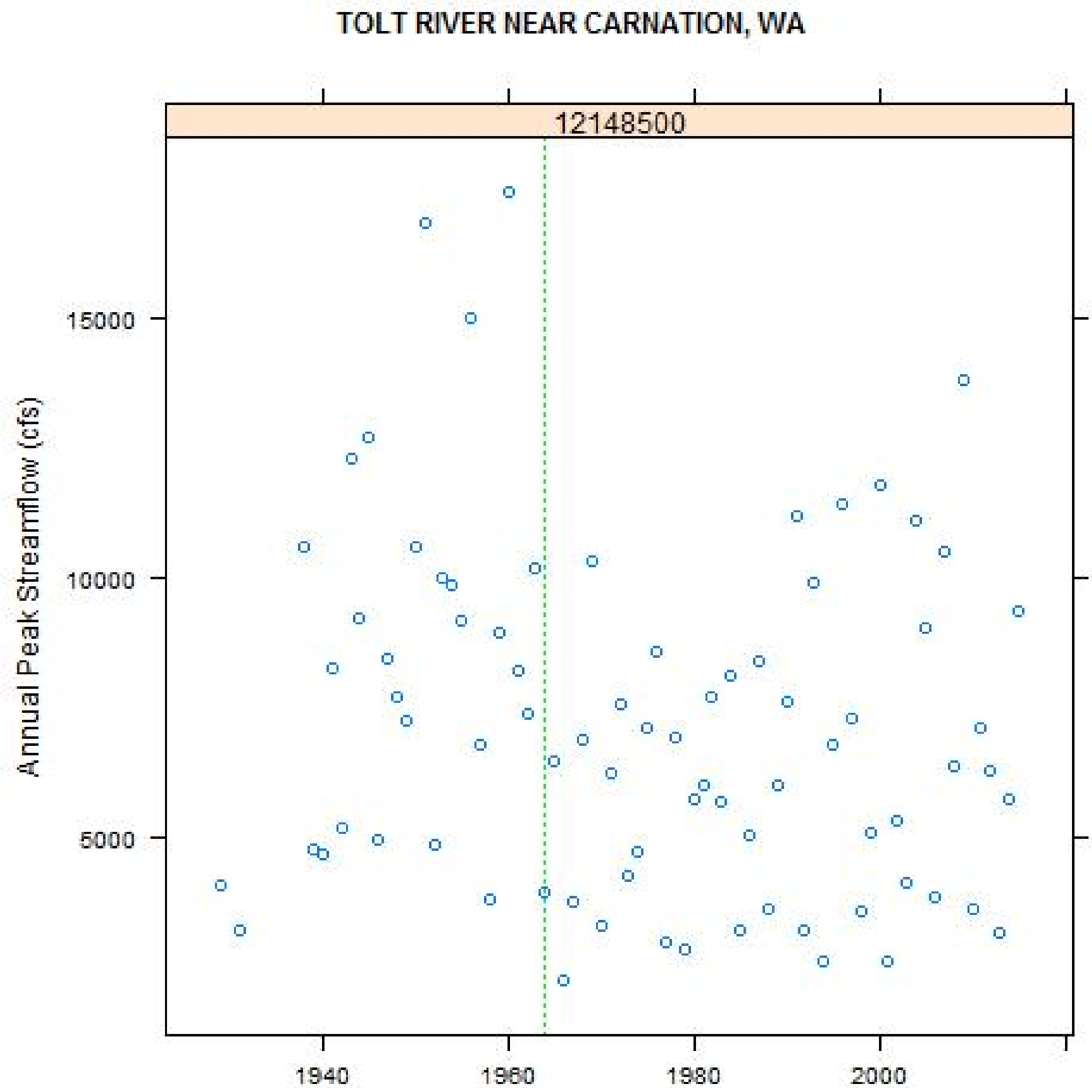

Figure A-10. Time series plot of annual instantaneous peak flow for the Tolt River near Carnation stream gaging station 12148500 (Note: Vertical green line indicates the start year of analysis).

REMARKS - Some regulation by South Fork Reservoir and by Seattle City Light hydroelectric project, upstream from station.

Considered regulated in the analyses presented in this report.

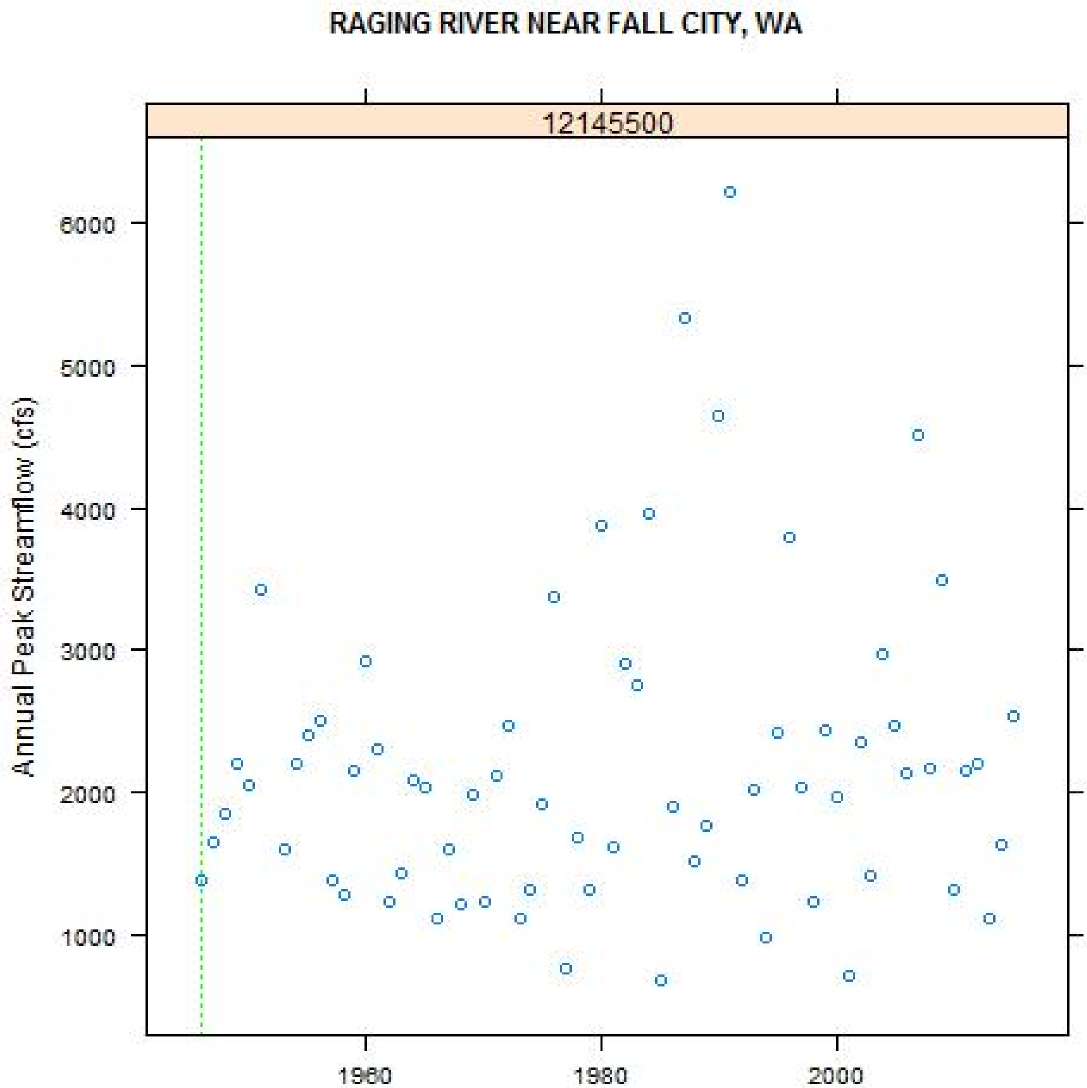

Figure A-11. Time series plot of annual instantaneous peak flow for the Raging River near Fall City stream gaging station 12145500 (Note: Vertical green line indicates the start year of analysis).

REMARKS - Some small diversions for irrigation and domestic use upstream from station. No regulation.

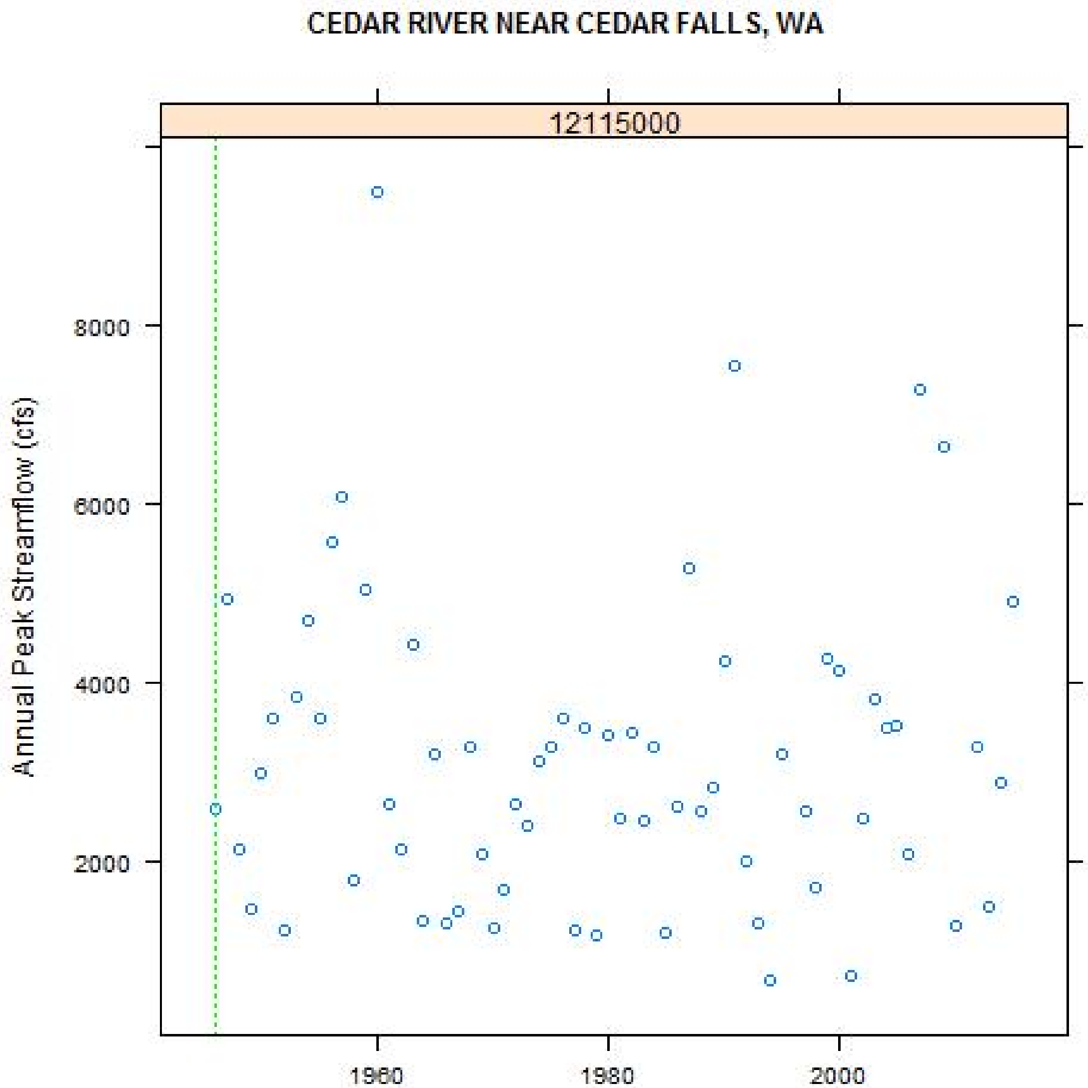

Figure A-12. Time series plot of annual instantaneous peak flow for the Cedar River near Cedar Falls stream gaging station 12115000 (Note: Vertical green line indicates the start year of analysis).

REMARKS - No regulation or diversion upstream from station.

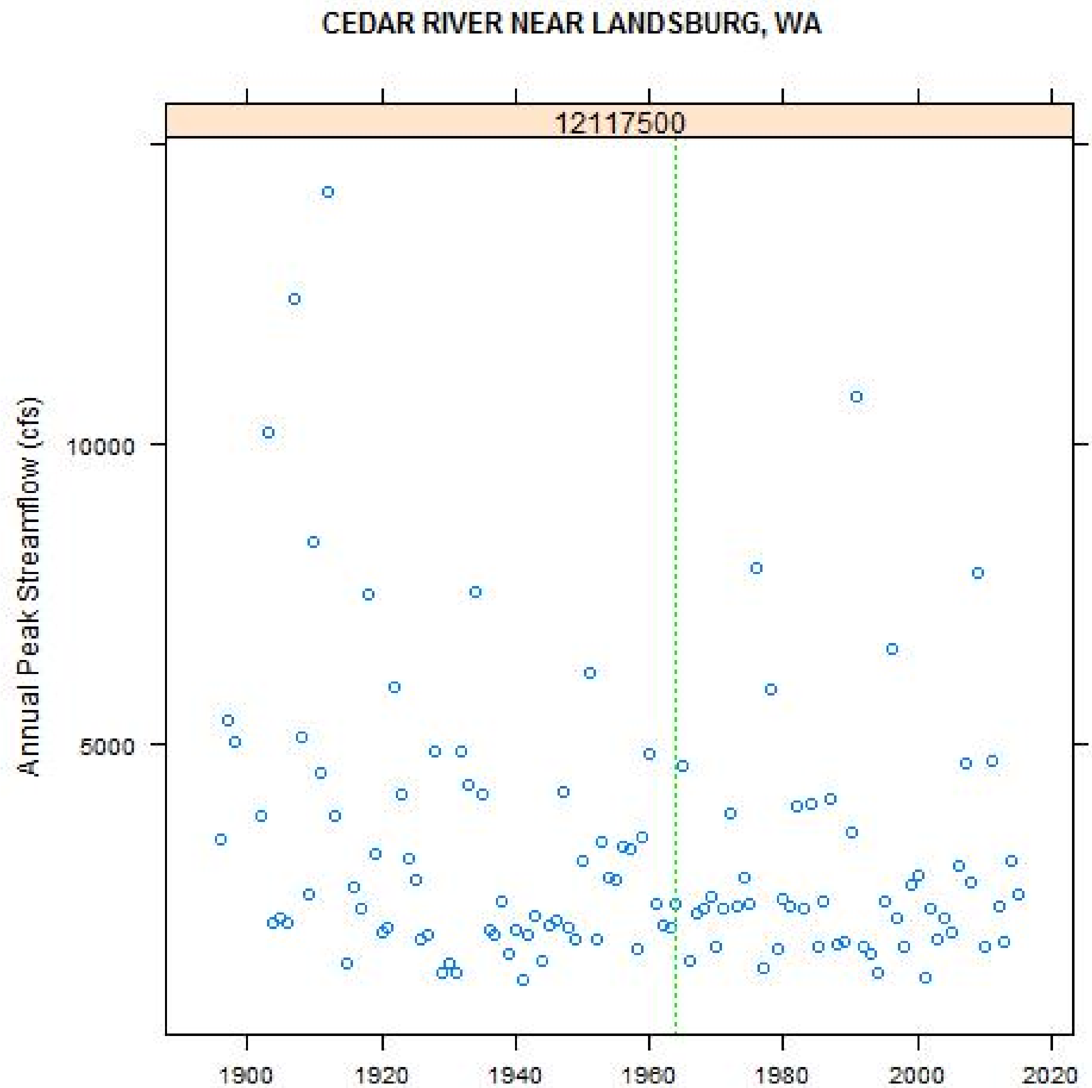

Figure A-13. Time series plot of annual instantaneous peak flow for the Cedar River near Landsburg stream gaging station 12117500 (Note: Vertical green line indicates the start year of analysis).

REMARKS - All diversions except Rock Creek returned to river upstream from station. Rock Creek, a tributary which entered naturally just upstream from station prior to 1932, is diverted during summer months to enter river at a point about 3.9 mi downstream from station. Some regulation by Chester Morse Lake (station 12115900) and Cedar Lake (station 12116060), 12.2 mi upstream.

Considered regulated in the analyses presented in this report.

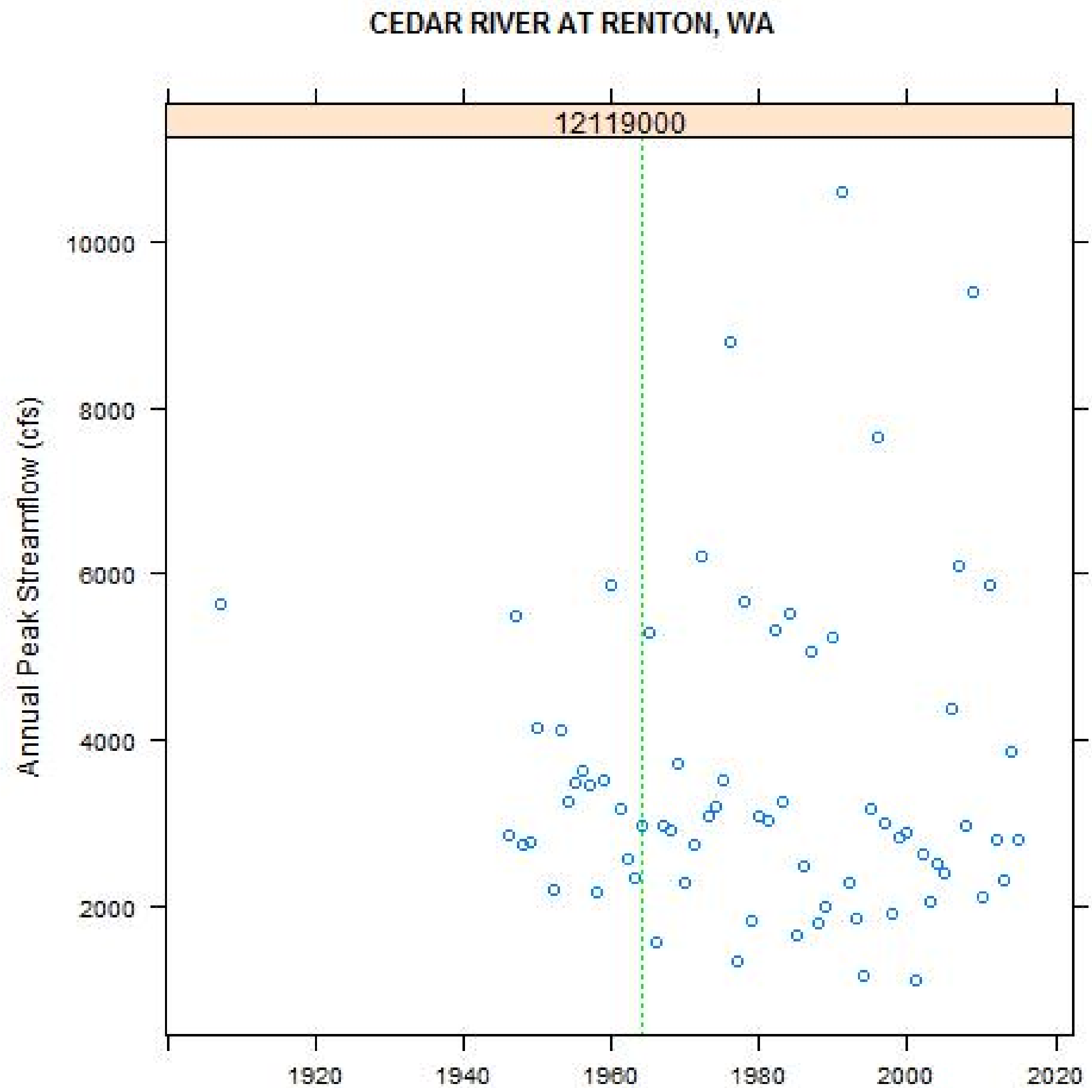

Figure A-14. Time series plot of annual instantaneous peak flow for the Cedar River at Renton stream gaging station 12119000 (Note: Vertical green line indicates the start year of analysis).

REMARKS - Flow partly regulated by Chester Morse Lake and Masonry Dam for operation of powerplant at Cedar Falls 32.1 mi upstream from gage.

Considered regulated in the analyses presented in this report.

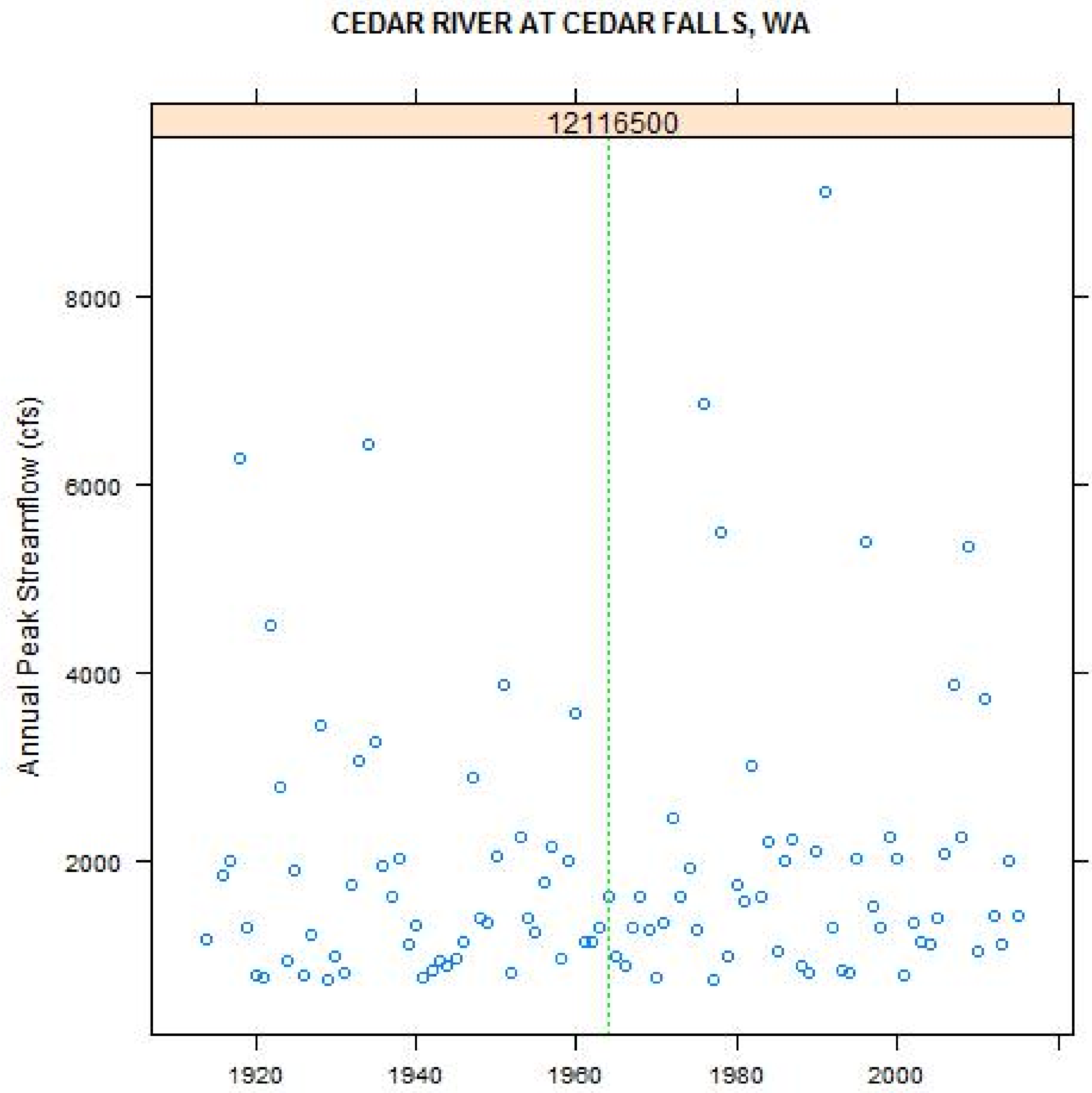

Figure A-15. Time series plot of annual instantaneous peak flow for the Cedar River at Cedar Falls stream gaging station 12116500 (Note: Vertical green line indicates the start year of analysis).

REMARKS - All diversions are returned to river upstream from station. Flow regulated by Chester Morse Lake (station 12115900) and Cedar Lake (station 12116060).

Considered regulated in the analyses presented in this report.

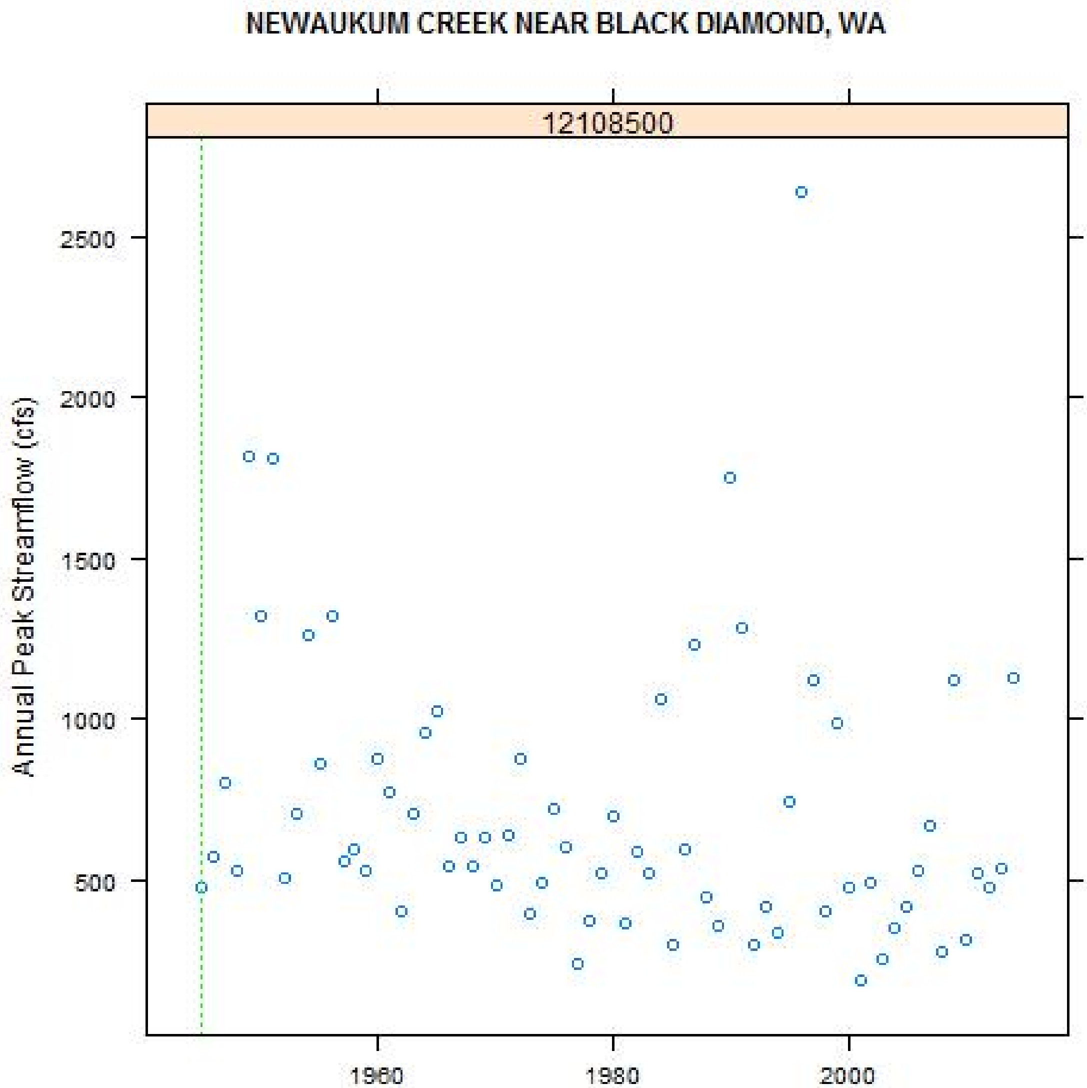

Figure A-16. Time series plot of annual instantaneous peak flow for the Newaukum Creek near Black Diamond stream gaging station 12108500 (Note: Vertical green line indicates the start year of analysis).

REMARKS - Many small diversions upstream from station for irrigation and domestic use. No regulation.

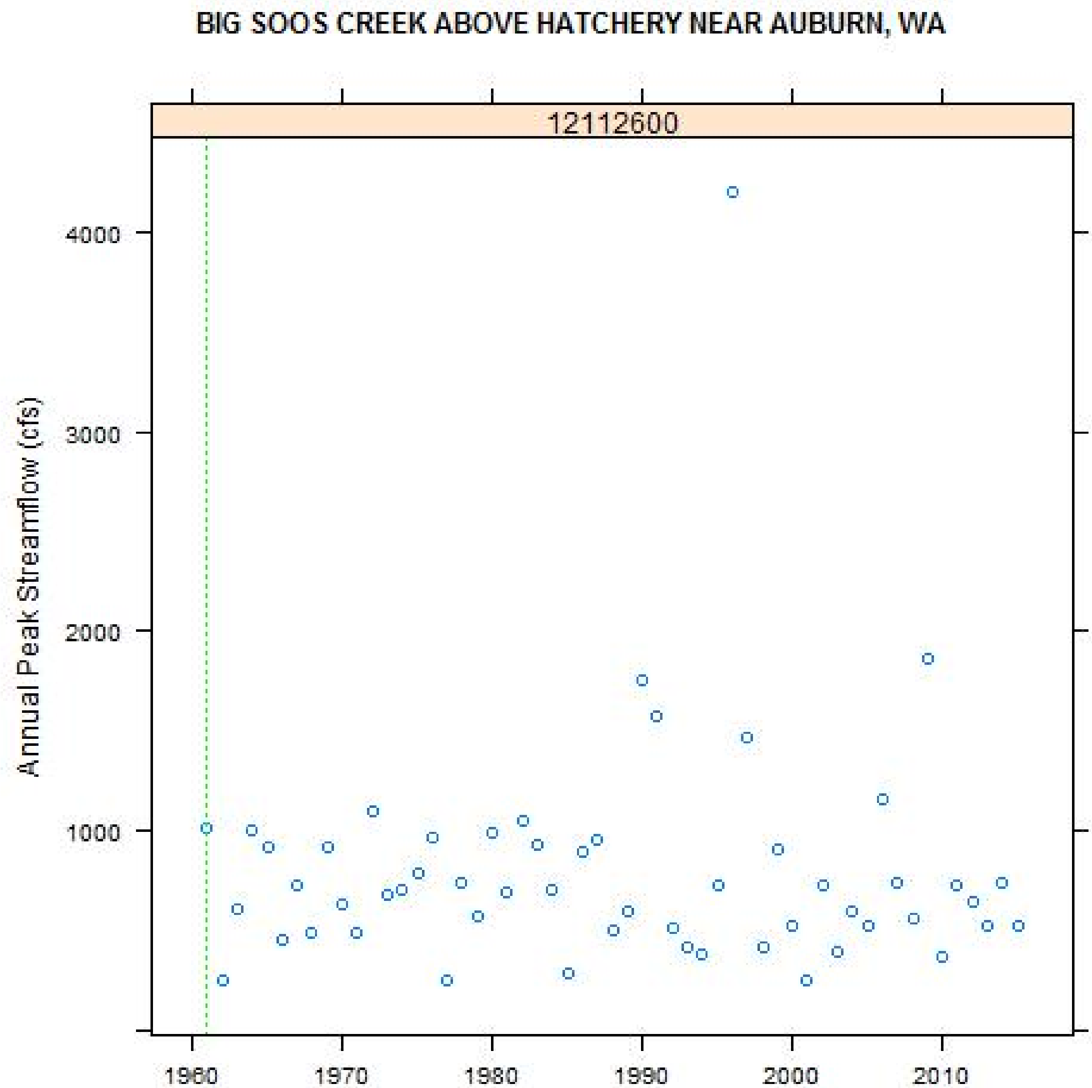

Figure A-17. Time series plot of annual instantaneous peak flow for the Big Soos Creek above hatchery stream gaging station 12112600 (Note: Vertical green line indicates the start year of analysis).

REMARKS - City of Seattle diverts probably less than 2 ft^3/s from Youngs Lake into Little Soos Creek, a tributary, during low flows. Prior to October 1966, fish hatchery 0.5 mi upstream from station diverted up to 19 ft^3/s which was returned downstream from the station.

Considered unregulated in the analyses presented in this report.

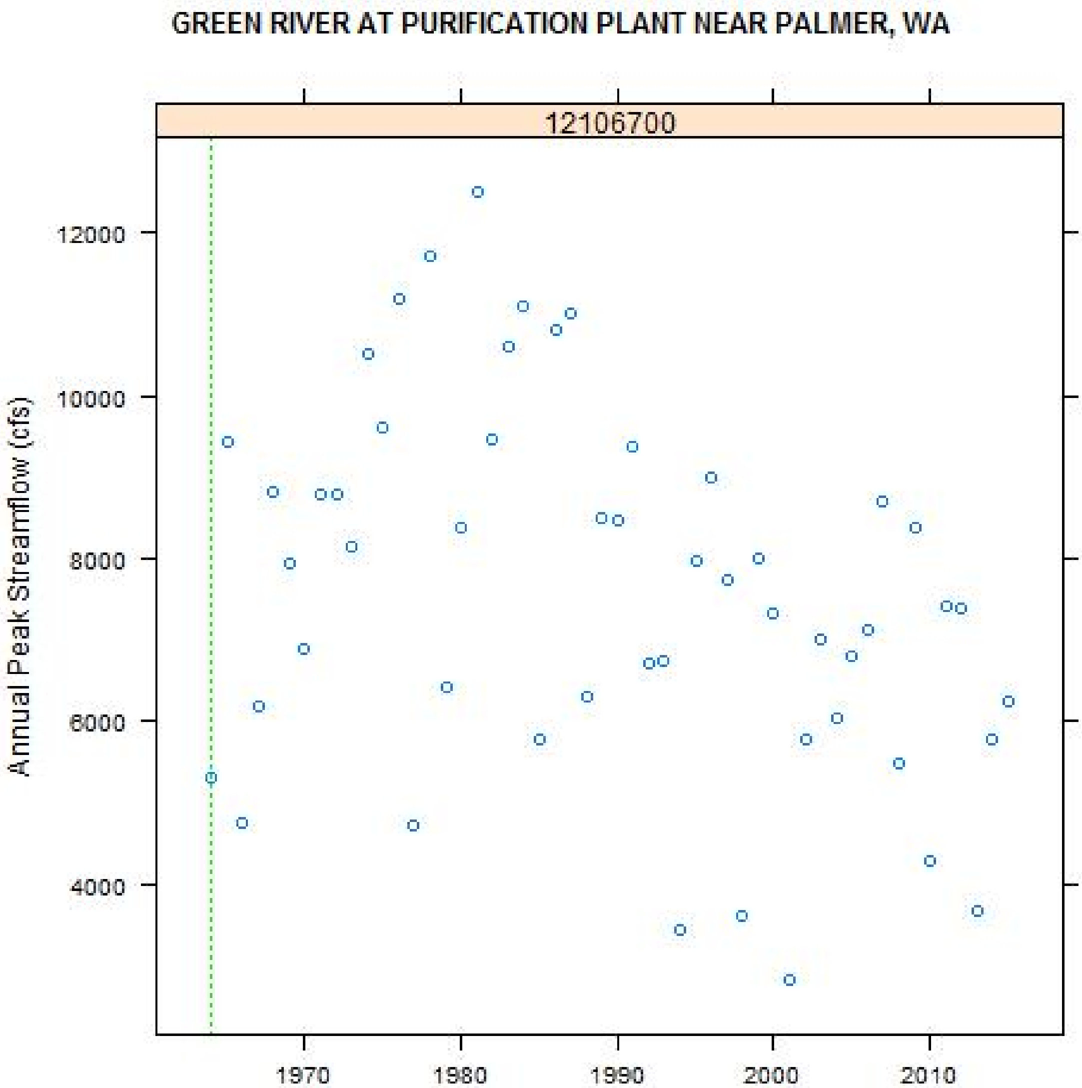

Figure A-18. Time series plot of annual instantaneous peak flow for the Green River at Purification Plant near Palmer stream gaging station 12106700 (Note: Vertical green line indicates the start year of analysis).

REMARKS - Since Dec. 5, 1961, flow regulated by Howard A. Hanson Reservoir (station 12105800), 4.1 mi upstream for flood control and during summer months to augment the natural river flow.

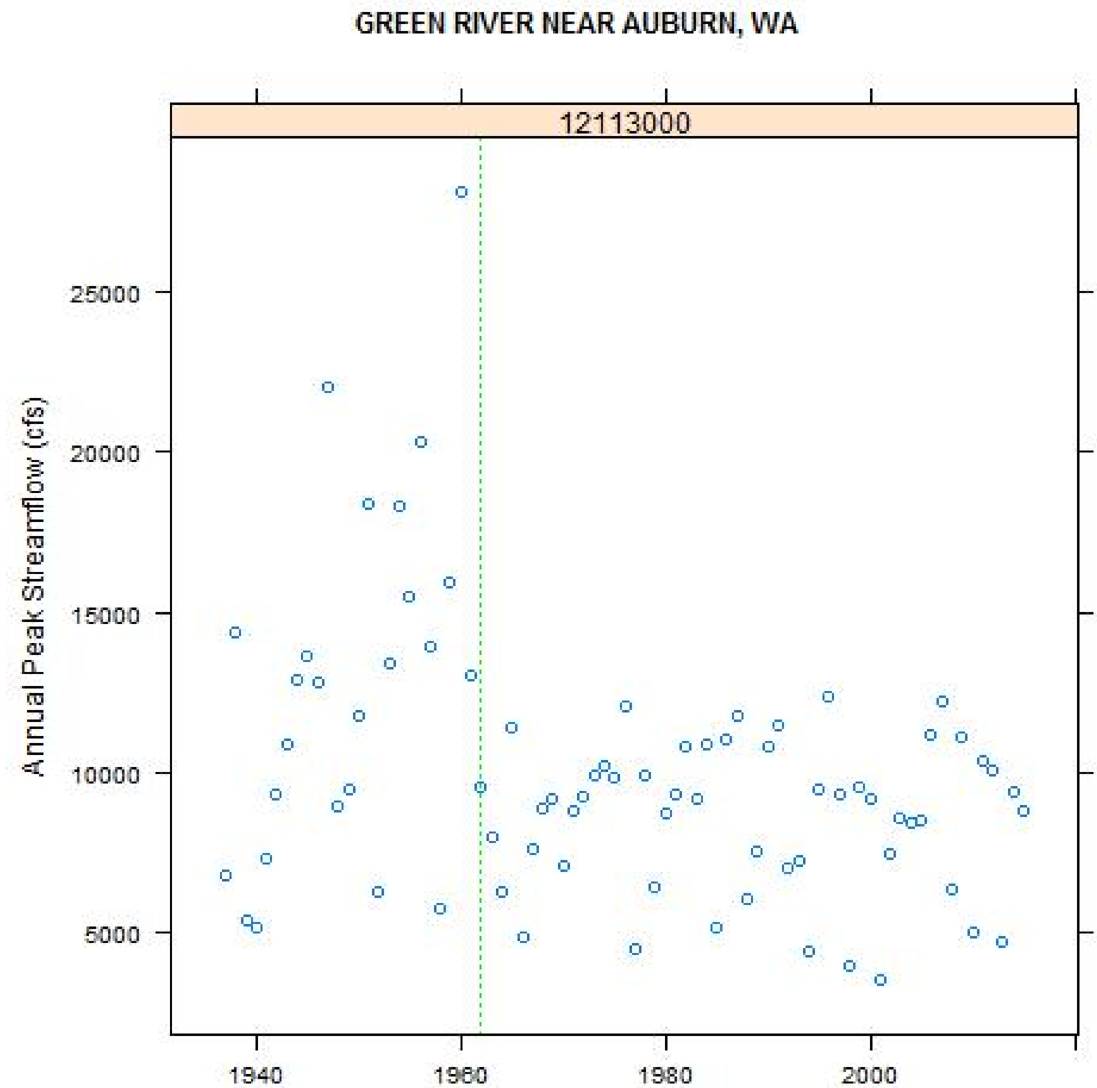

Figure A-19. Time series plot of annual instantaneous peak flow for the Green River near Auburn stream gaging station 12113000 (Note: Vertical green line indicates the start year of analysis).

REMARKS - Since Dec. 5, 1961, flow regulated by Howard A. Hanson Reservoir (station 12105800), 32.5 mi upstream from station, for flood control and during summer months, to augment the natural river flow. Minor diversions on upstream tributaries for domestic use.

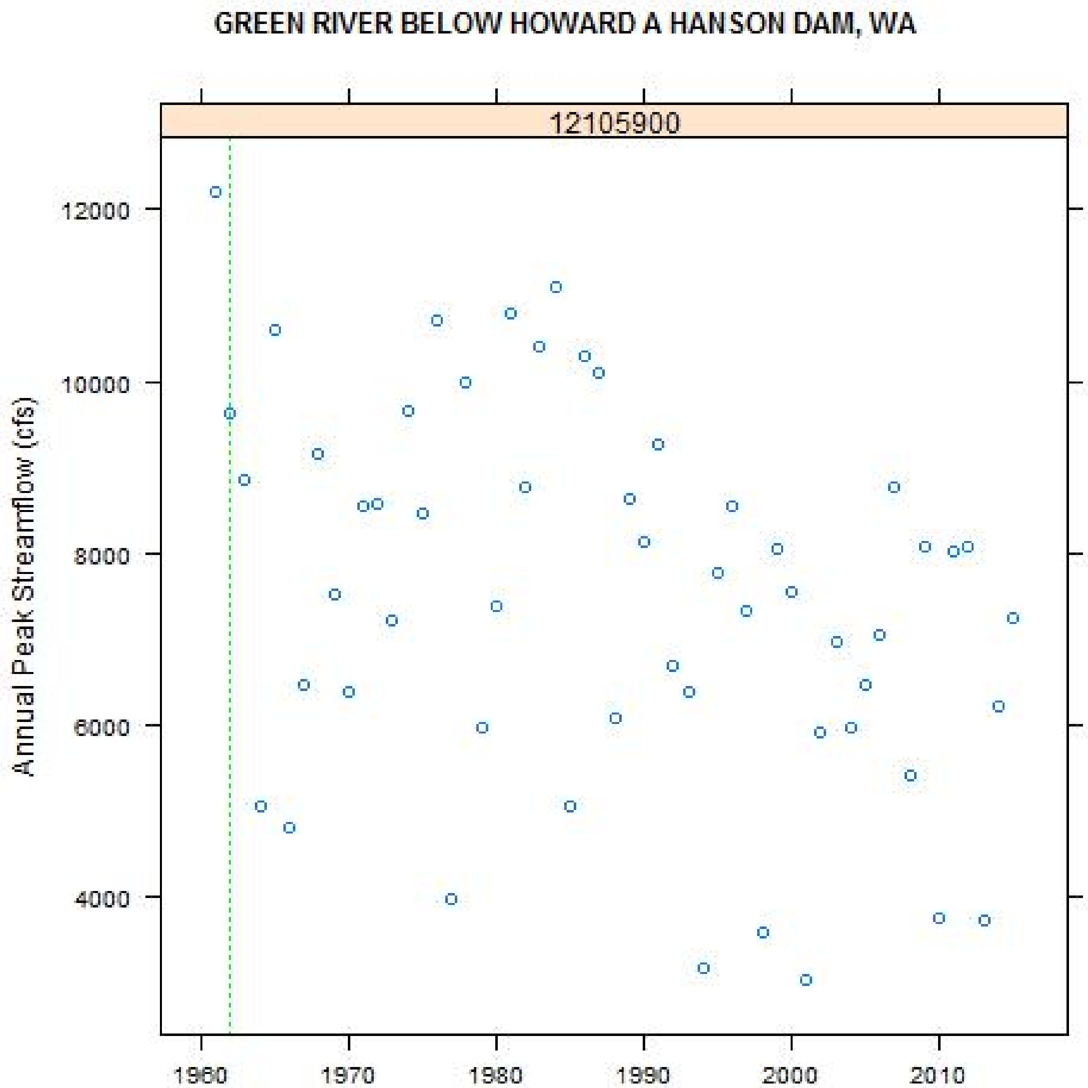

Figure A-20. Time series plot of annual instantaneous peak flow for the Green River below Howard Hanson stream gaging station 12105900 (Note: Vertical green line indicates the start year of analysis).

REMARKS - Flow regulated by Howard A. Hanson Reservoir (station 12105800) for flood control and during summer months to augment the natural river flow.

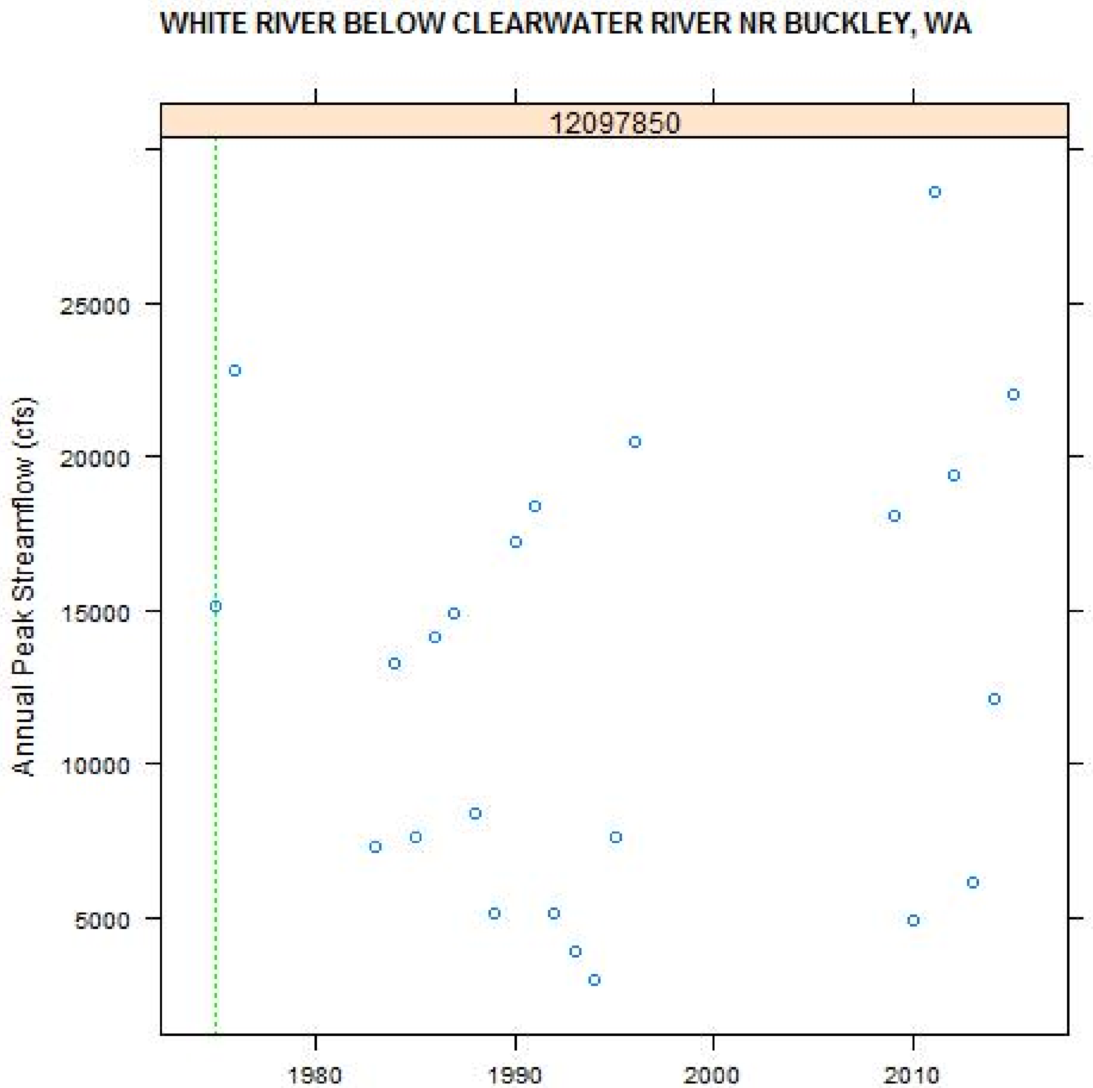

Figure A-21. Time series plot of annual instantaneous peak flow for the White River below Clearwater stream gaging station 12097850 (Note: Vertical green line indicates the start year of analysis).

REMARKS - No regulation or diversion upstream from station.

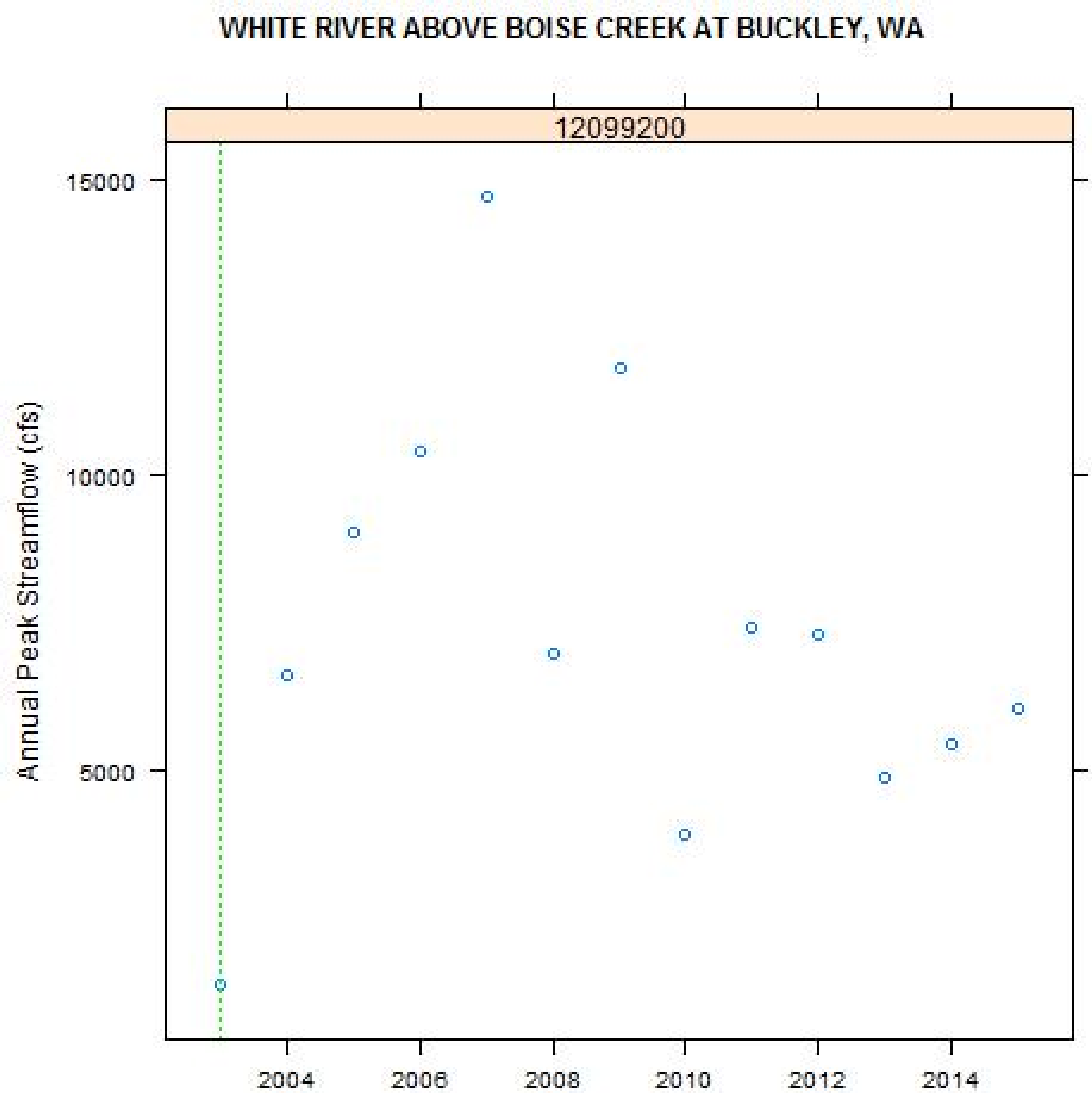

Figure A-22. Time series plot of annual instantaneous peak flow for the White River above Boise Creek stream gaging station 12099200 (Note: Vertical green line indicates the start year of analysis).

REMARKS - Since November 1911, White River Canal has diverted water from left bank, 1,500 ft upstream, for storage in Lake Tapps. Water is returned to the White River 20.3 mi downstream via Lake Tapps Diversion, after power development at Dieringer Powerplant. Since 1942, flows have been regulated by Mud Mountain Dam for flood control.

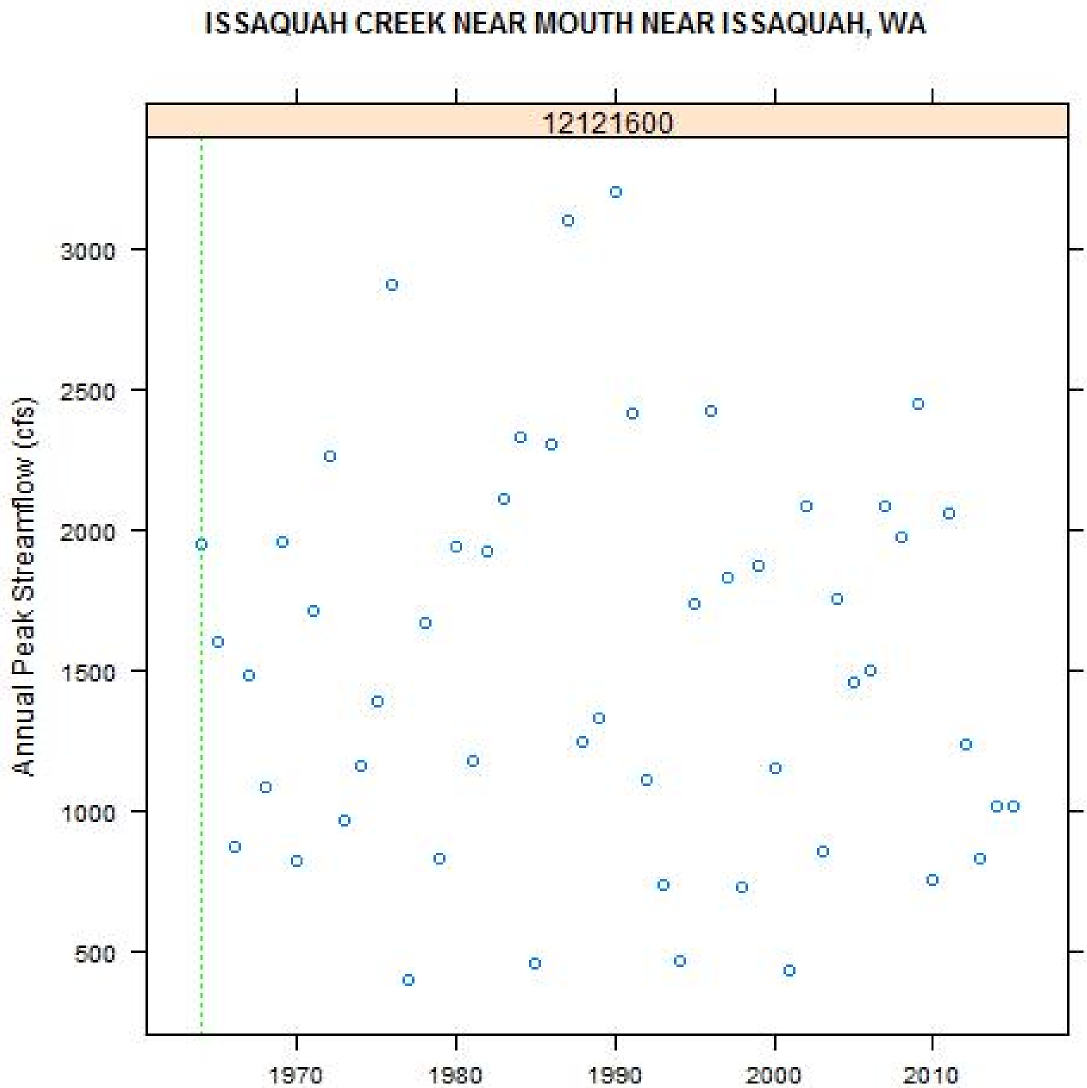

Figure A-23. Time series plot of annual instantaneous peak flow for the Issaquah Creek near Issaquah stream gaging station 12121600 (Note: Vertical green line indicates the start year of analysis).

REMARKS - Many minor diversions for irrigation and domestic use upstream from station.

Considered unregulated in the analyses presented in this report.

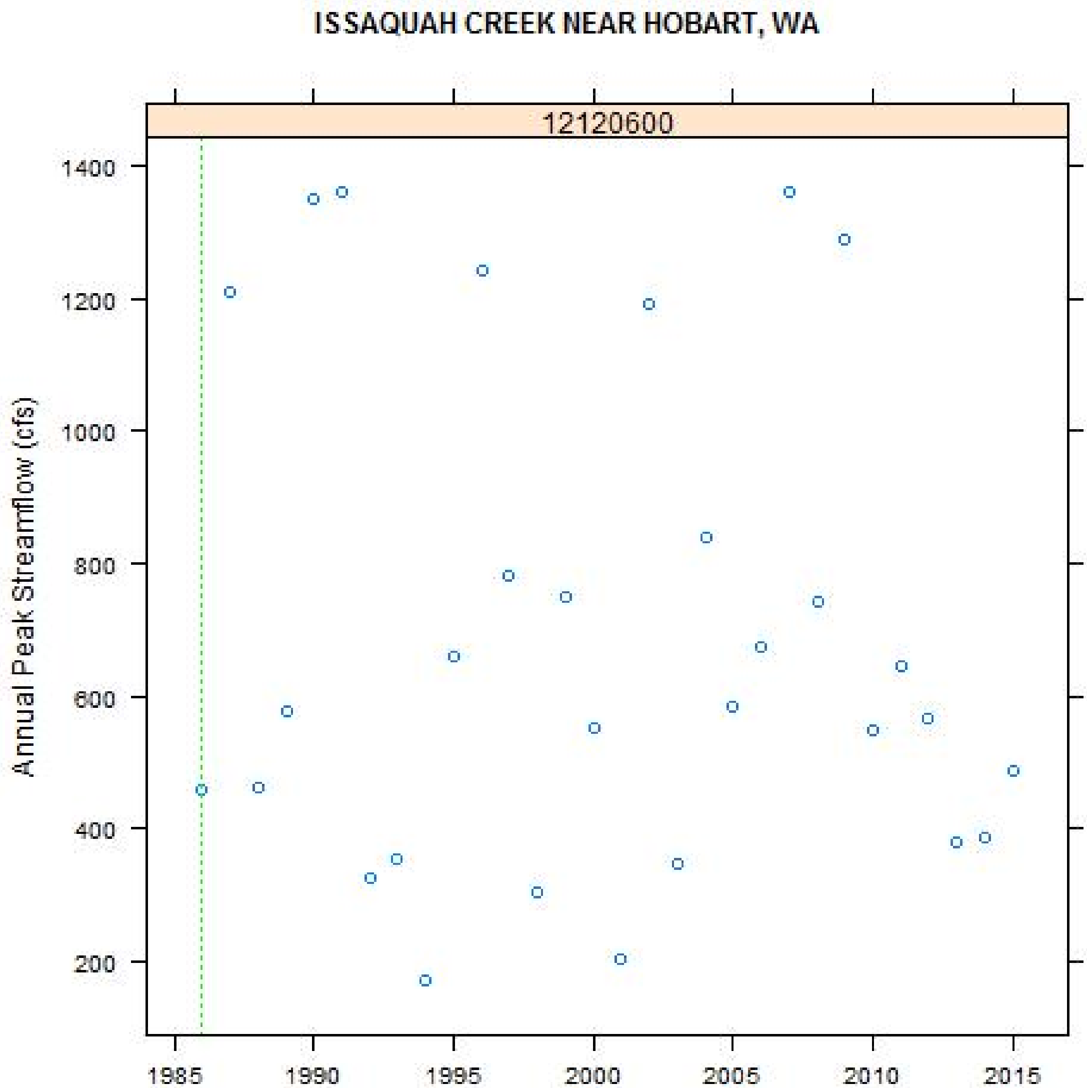

Figure A-24. Time series plot of annual instantaneous peak flow for the Issaquah Creek near Hobart stream gaging station 12120600 (Note: Vertical green line indicates the start year of analysis).

REMARKS - No known regulation or diversion upstream from station.

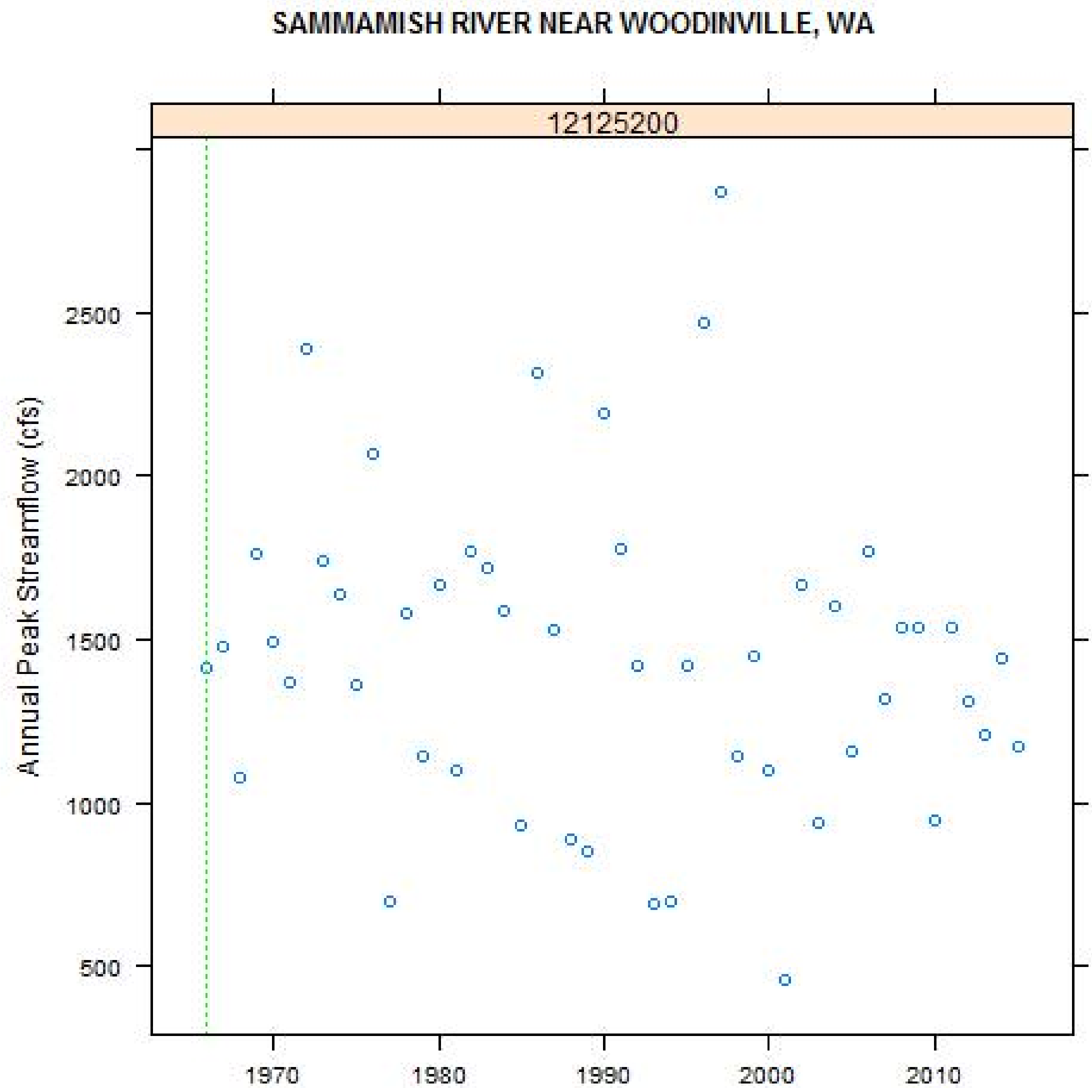

Figure A-25. Time series plot of annual instantaneous peak flow for the Sammamish River near Woodinville stream gaging station 12125200 (Note: Vertical green line indicates the start year of analysis).

REMARKS - Records fair, except for those above 1,000 ft^3/s which are poor. Some regulation at Sammamish Lake. Many small diversions for irrigation and domestic use.

Considered regulated in the analyses presented in this report.

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Appendix B: Matlab Method 17B Flow Frequency Analysis Plots

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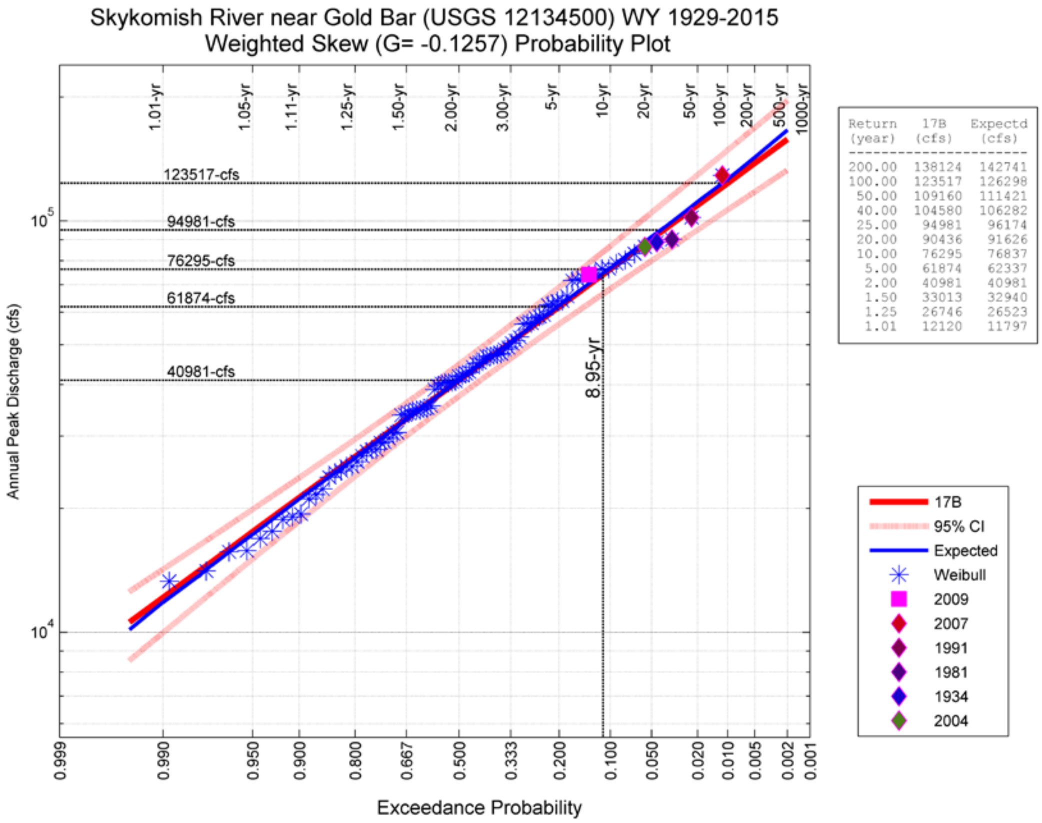


Figure B-1. Flood-frequency plot for the Skykomish River near Gold Bar streamflow gaging station 12134500, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - No regulation. Several small diversions upstream from station.

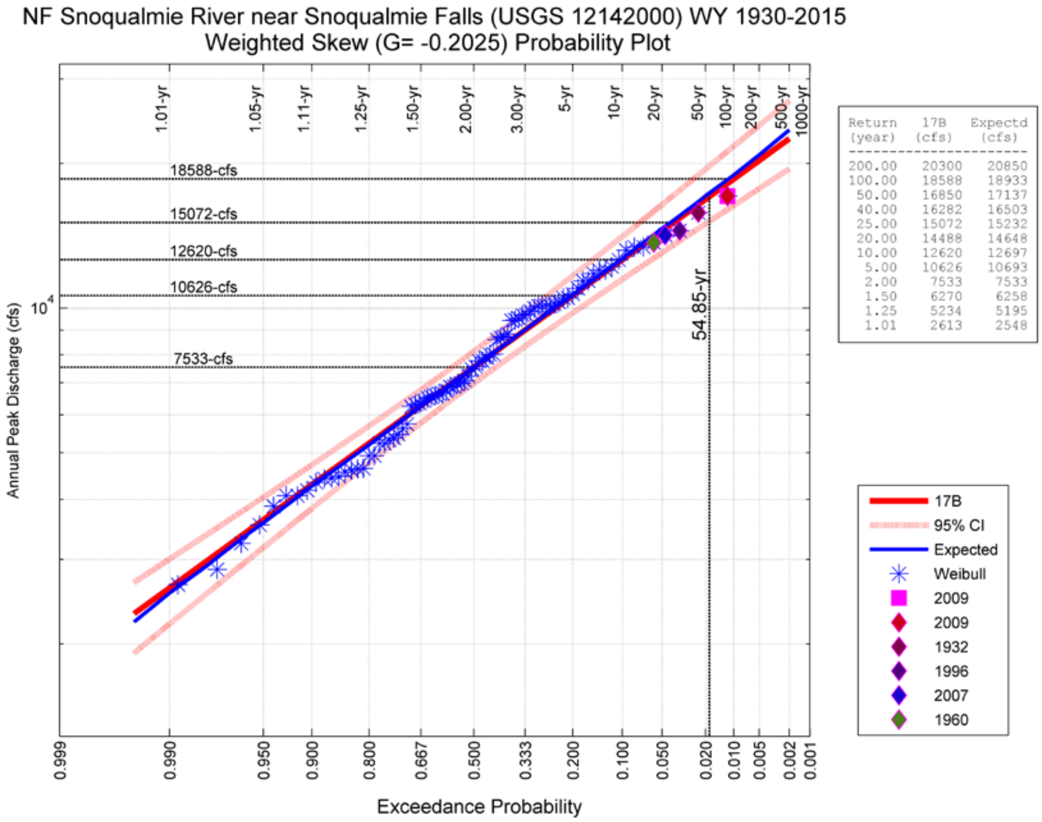


Figure B-2. Flood-frequency plot for the North Fork Snoqualmie River near Snoqualmie Falls streamflow gaging station 12142000, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - No regulation or diversion upstream from station.

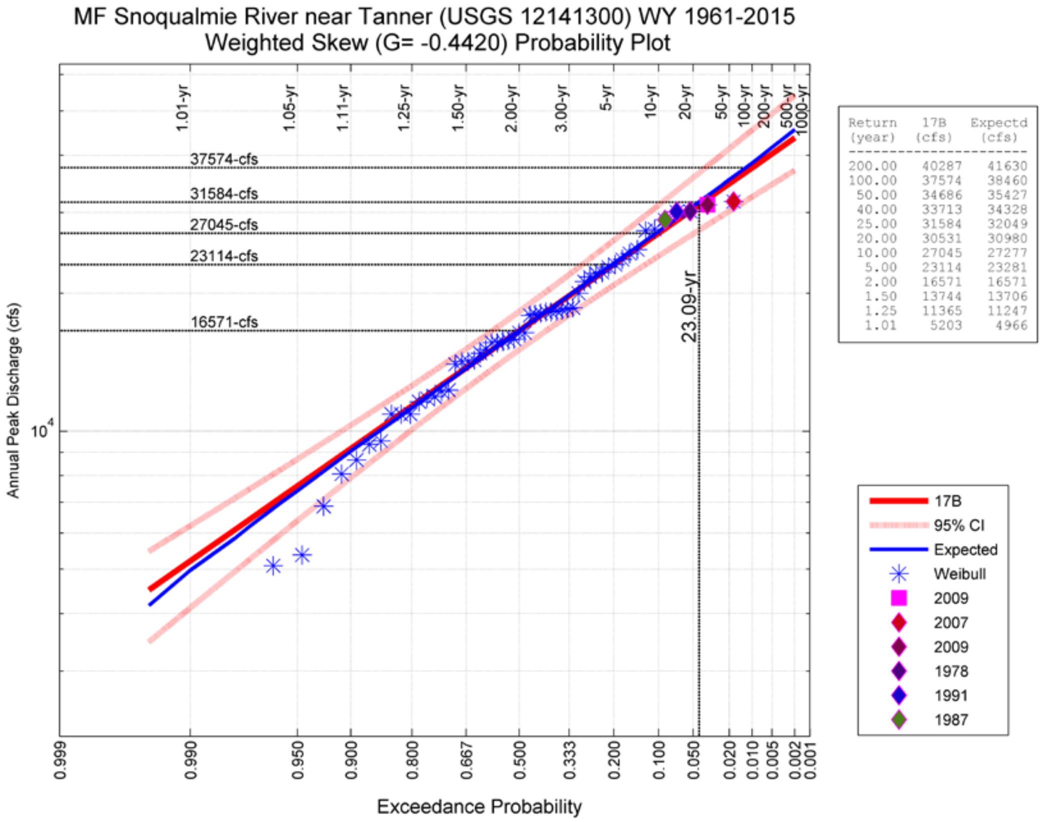
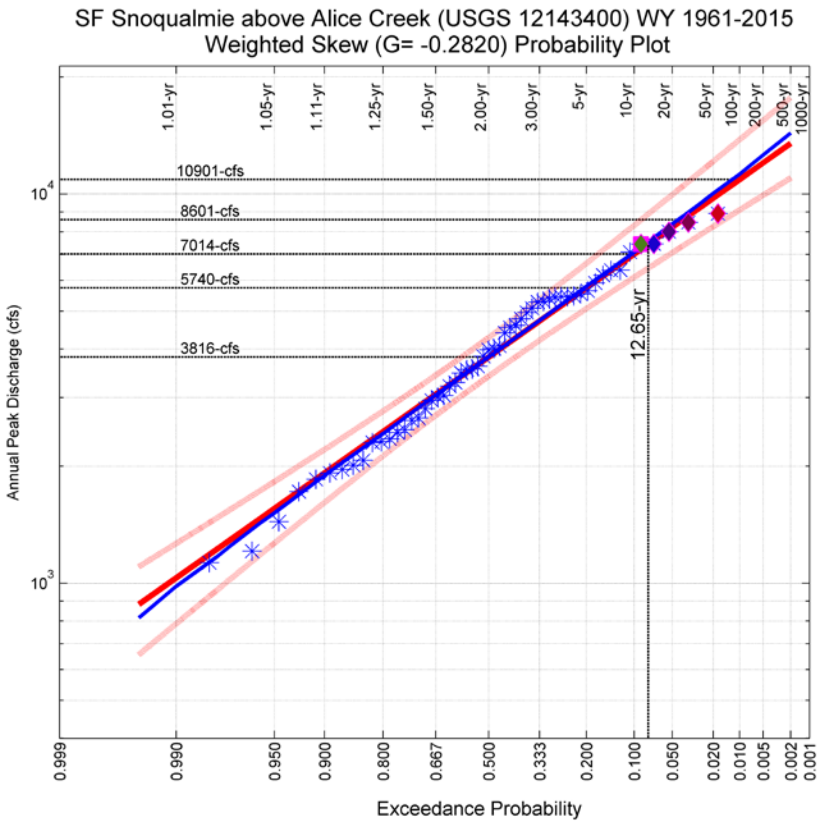


Figure B-3. Flood-frequency plot for the Middle Fork Snoqualmie River near Tanner streamflow gaging station 12141300, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

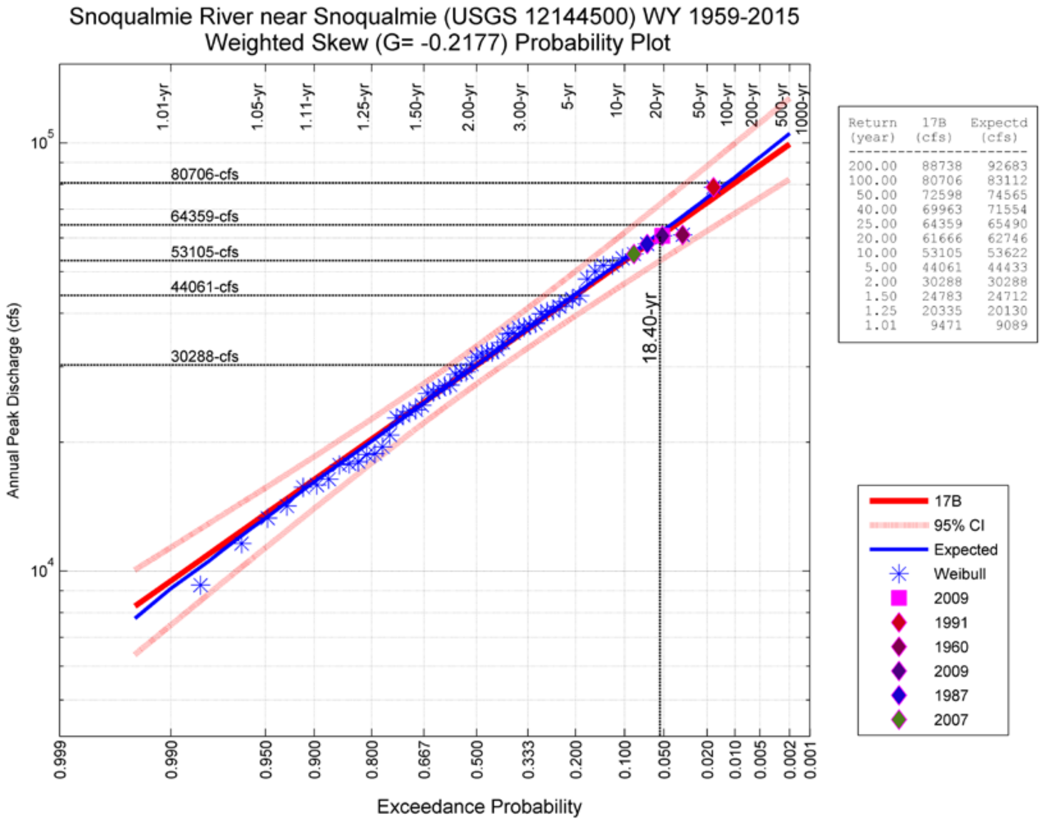
REMARKS - No regulation or diversion upstream from station.



Return (year)	17B (cfs)	Expectd (cfs)
200.00	12026	12598
100.00	10901	11252
50.00	9761	10047
40.00	9390	9622
25.00	8601	8767
20.00	8221	8379
10.00	7014	7090
5.00	5740	5793
2.00	3816	3816
1.50	3057	3047
1.25	2452	2424
1.01	1030	981

Figure B-4. Flood-frequency plot for the South Fork Snoqualmie above Alice Creek streamflow gaging station 12143400, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - No regulation or diversion upstream from station.



Return (year)	17B (cfs)	Expectd (cfs)
200.00	88738	92683
100.00	80706	83112
50.00	72598	74565
40.00	69963	71554
25.00	64359	65490
20.00	61666	62746
10.00	53105	53622
5.00	44061	44433
2.00	30288	30288
1.50	24783	24712
1.25	20335	20130
1.01	9471	9089

Figure B-5. Flood-frequency plot for the Snoqualmie River near Snoqualmie streamflow gaging station 12144500, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - Medium and low flows affected by powerplant 0.1 mi upstream from station. Considered unregulated in the analyses presented in this report.

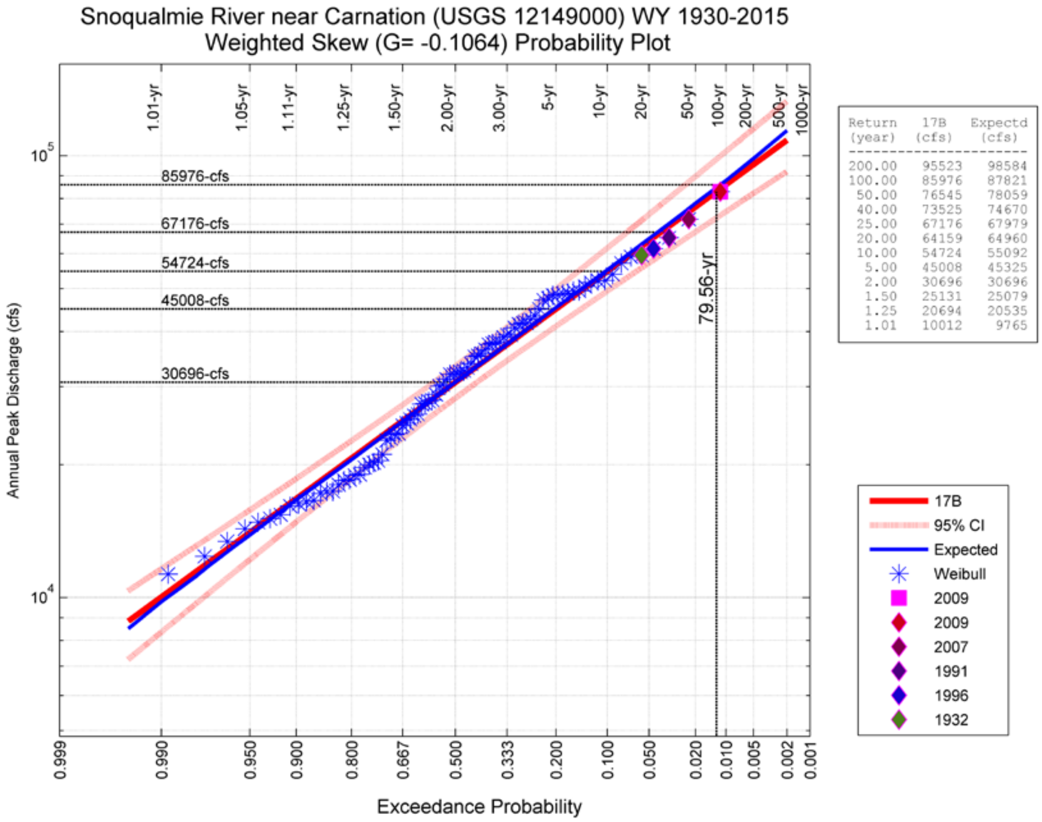


Figure B-6. Flood-frequency plot for the Snoqualmie River near Carnation streamflow gaging station 12149000, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - Seattle Water Department diverts water upstream from station from South Fork Tolt River for municipal use. Several small diversions for irrigation and domestic use upstream from station. Some pondage at Snoqualmie Falls and some diurnal fluctuation caused by powerplant.

Considered unregulated in the analyses presented in this report.

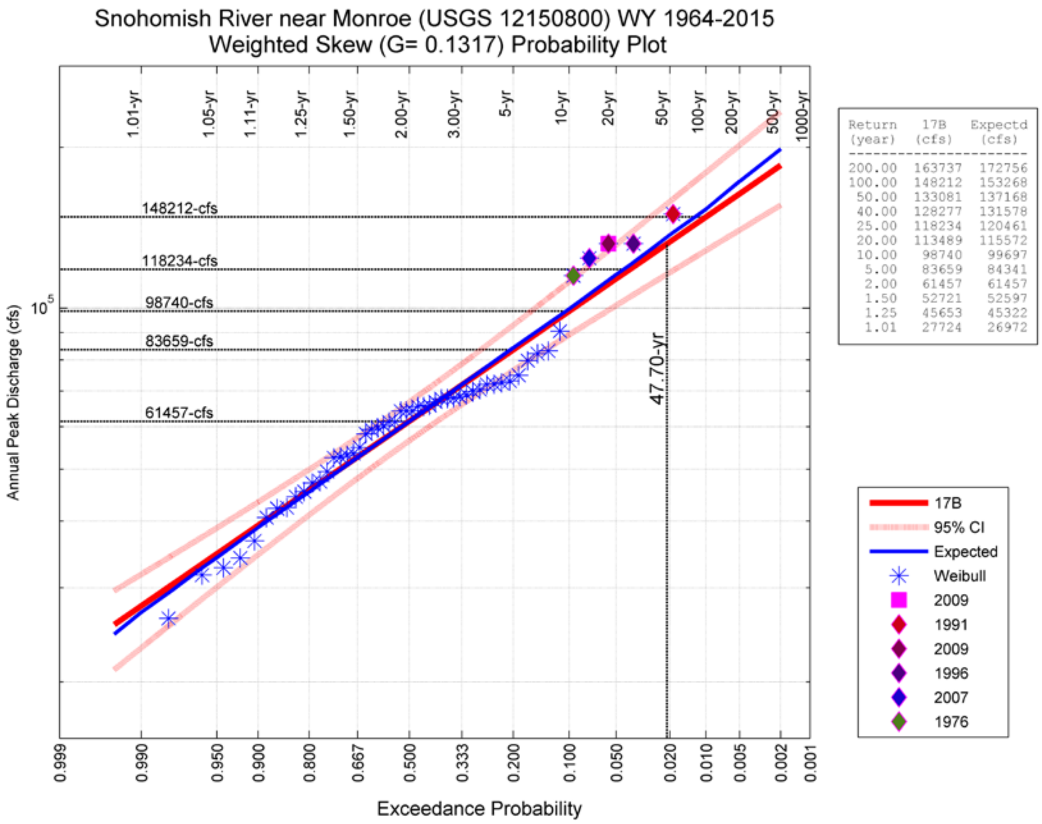


Figure B-7. Flood-frequency plot for the Snohomish River near Monroe streamflow gaging station 12150800, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - Some regulation by powerplant at Snoqualmie Falls, 40 mi upstream, and by Spada Lake, 30 mi upstream. Minor diversions for irrigation returned to river upstream from gage. Seattle Water Department diverts water upstream from station from South Fork Tolt River for municipal use and the City of Everett diverts water upstream from the station from Sultan River for municipal use.

Considered unregulated in the analyses presented in this report.

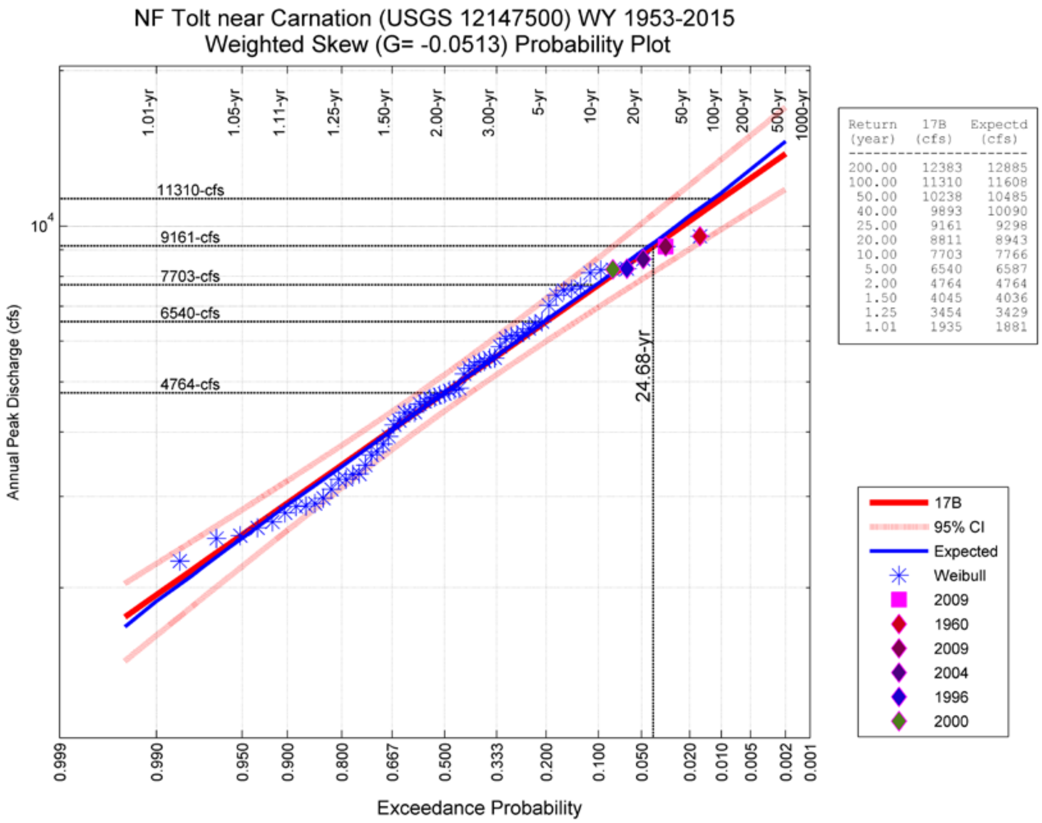


Figure B-8. Flood-frequency plot for the North Fork Tolt near Carnation streamflow gaging station 12147500, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - No regulation or diversion upstream from station.

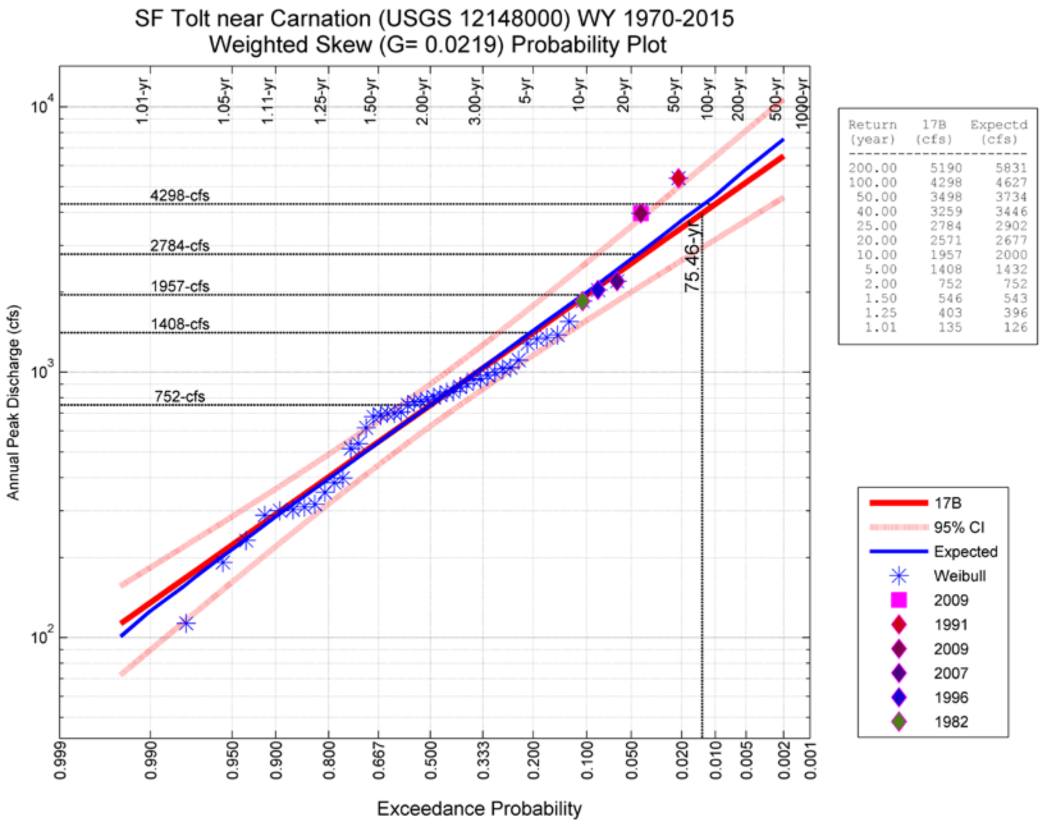


Figure B-9. Flood-frequency plot for the South Fork Tolt near Carnation streamflow gaging station 12148000, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - Regulation by South Fork Tolt Reservoir since September 1963.

Considered regulated in the analyses presented in this report.

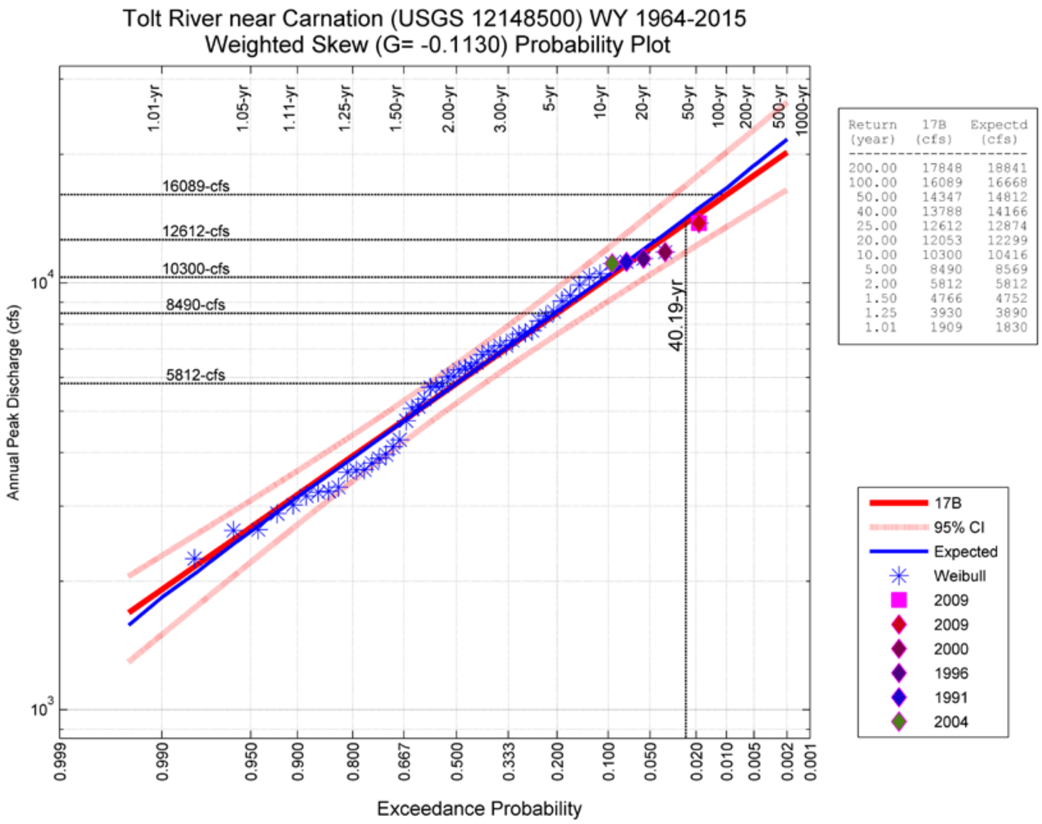
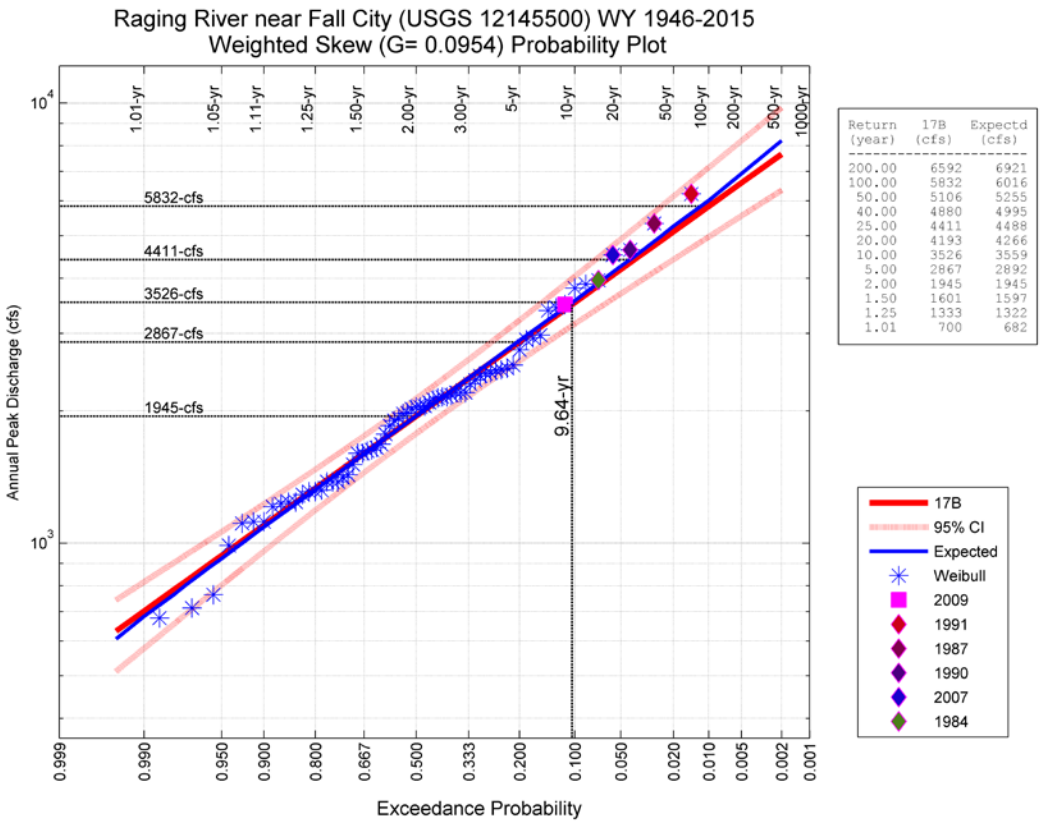


Figure B-10. Flood-frequency plot for the Tolt River near Carnation streamflow gaging stations 12148500, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - Some regulation by South Fork Reservoir and by Seattle City Light hydroelectric project, upstream from station.

Considered regulated in the analyses presented in this report.



Return (year)	17B (cfs)	Expectd (cfs)
200.00	6592	6921
100.00	5832	6016
50.00	5106	5255
40.00	4880	4995
25.00	4411	4488
20.00	4193	4266
10.00	3526	3559
5.00	2867	2892
2.00	1945	1945
1.50	1601	1597
1.25	1333	1322
1.01	700	682

Figure B-11. Flood-frequency plot for the Raging River near Fall City streamflow gaging station 12145500, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - Some small diversions for irrigation and domestic use upstream from station. No regulation.

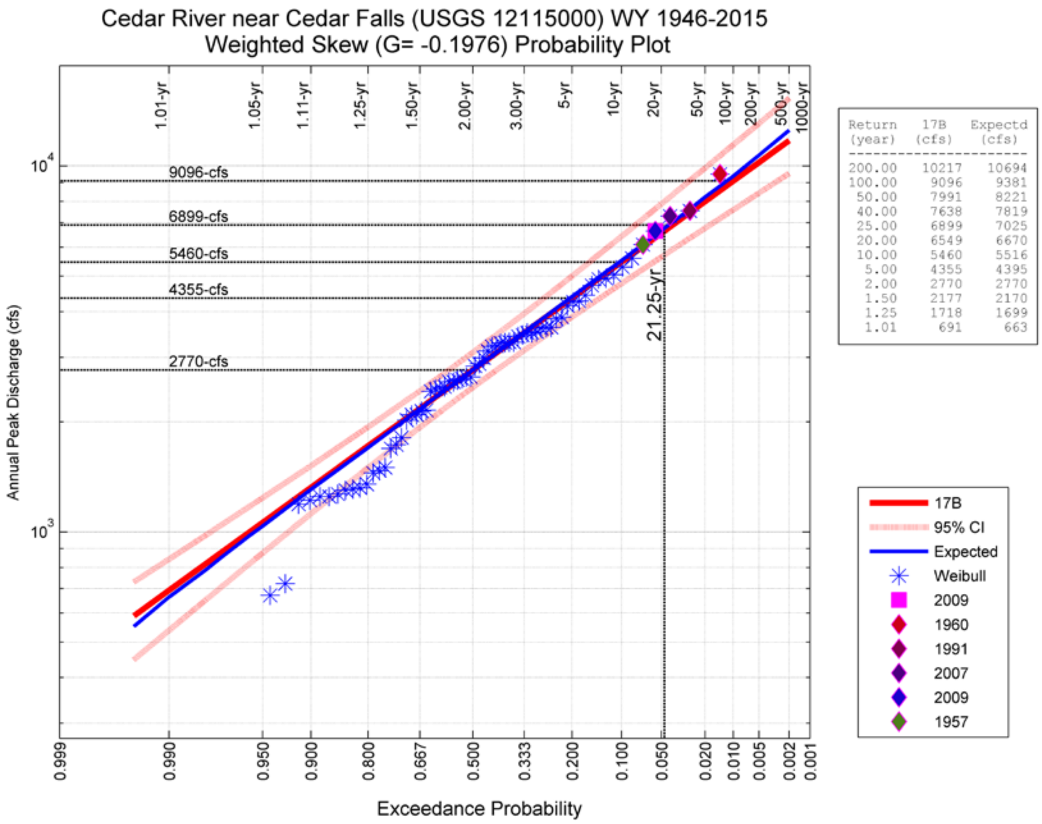


Figure B-12. Flood-frequency plot for the Cedar River near Cedar Falls streamflow gaging station 12115000, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - No regulation or diversion upstream from station.

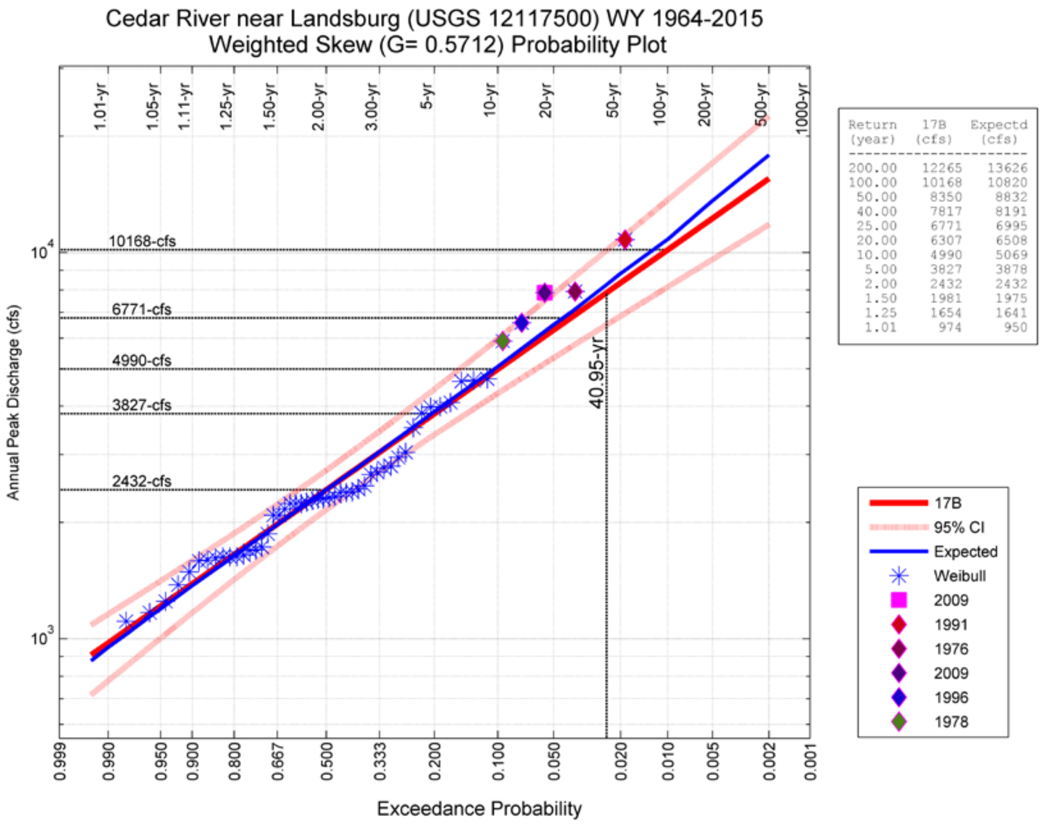


Figure B-13. Flood-frequency plot for the Cedar River near Landsburg streamflow gaging station 12117500, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - All diversions except Rock Creek returned to river upstream from station. Rock Creek, a tributary which entered naturally just upstream from station prior to 1932, is diverted during summer months to enter river at a point about 3.9 mi downstream from station. Some regulation by Chester Morse Lake (station 12115900) and Cedar Lake (station 12116060), 12.2 mi upstream.

Considered regulated in the analyses presented in this report.

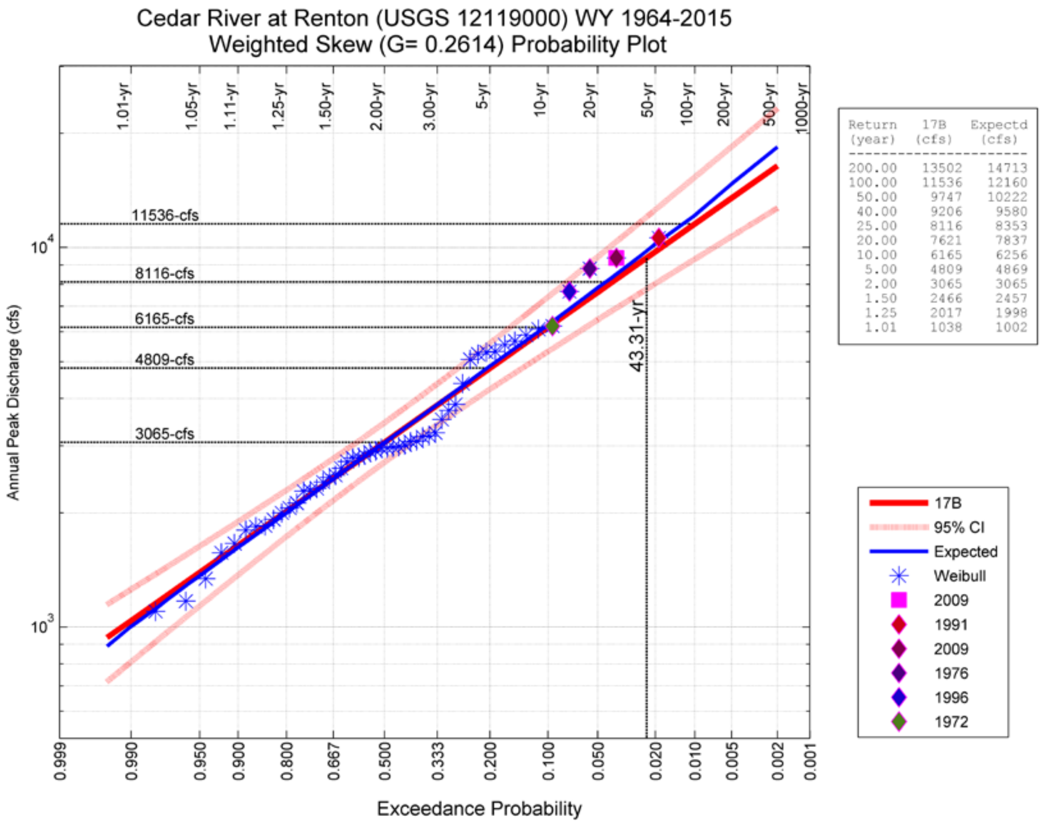
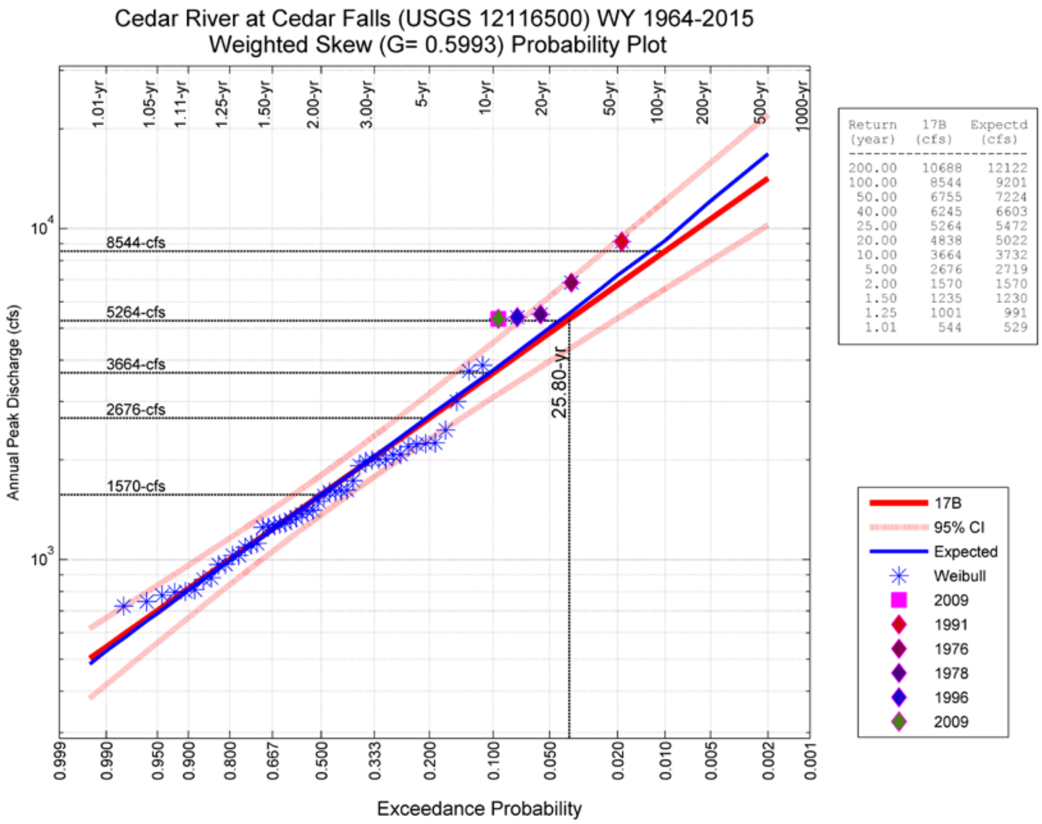


Figure B-14. Flood-frequency plot for the Cedar River at Renton streamflow gaging station 12119000, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - Flow partly regulated by Chester Morse Lake and Masonry Dam for operation of powerplant at Cedar Falls 32.1 mi upstream from gage.

Considered regulated in the analyses presented in this report.



Return (year)	17B (cfs)	Expectd (cfs)
200.00	10688	12122
100.00	8544	9201
50.00	6755	7224
40.00	6245	6603
25.00	5264	5472
20.00	4838	5022
10.00	3664	3732
5.00	2676	2719
2.00	1570	1570
1.50	1235	1230
1.25	1001	991
1.01	544	529

Figure B-15. Flood-frequency plot for the Cedar River at Cedar Falls streamflow gaging staton 12116500, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - All diversions are returned to river upstream from station. Flow regulated by Chester Morse Lake (station 12115900) and Cedar Lake (station 12116060).

Considered regulated in the analyses presented in this report.

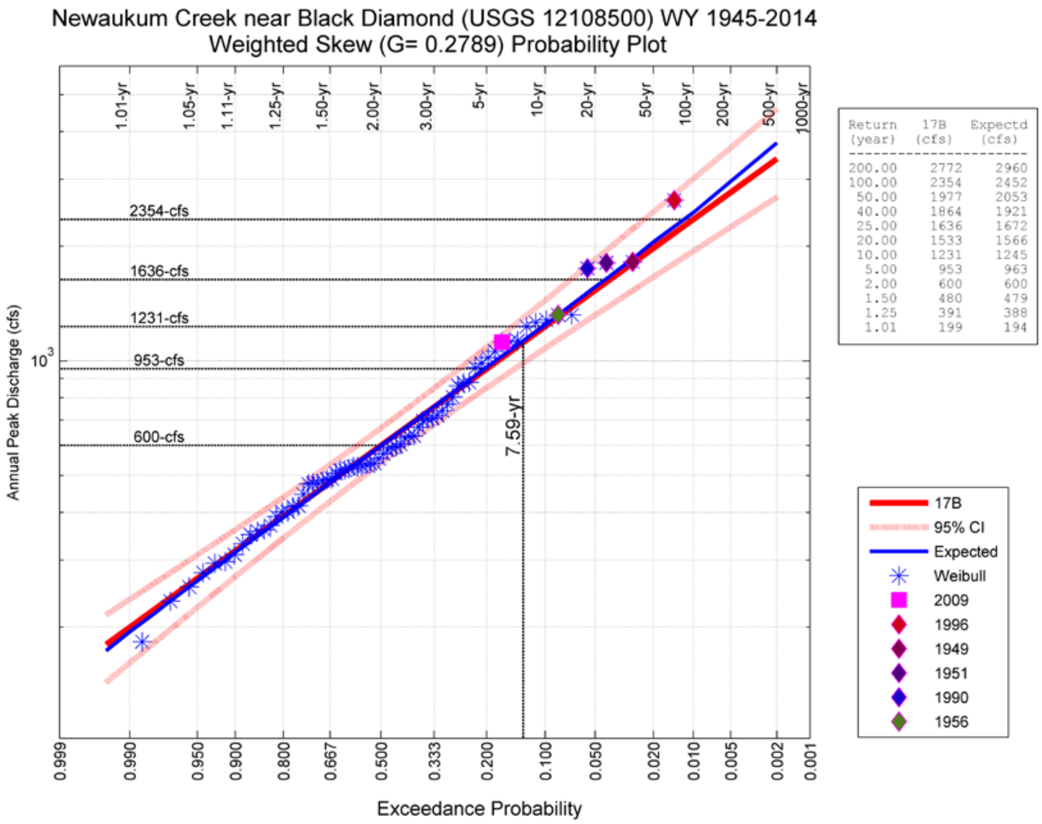


Figure B-16. Flood-frequency plot for the Newaukum Creek near Black Diamond streamflow gaging station 12108500, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2014.

REMARKS - Many small diversions upstream from station for irrigation and domestic use. No regulation.

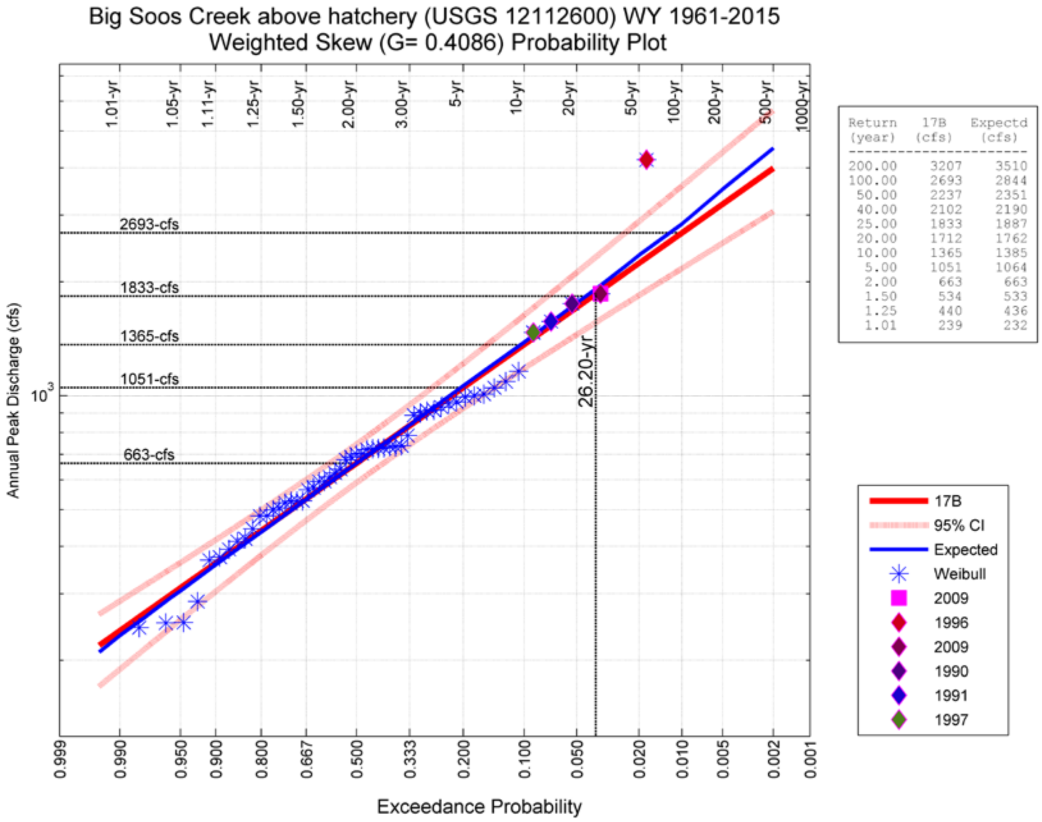


Figure B-17. Flood-frequency plot for the Big Soos Creek above hatchery streamflow gaging station 12112600, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - City of Seattle diverts probably less than 2 ft³/s from Youngs Lake into Little Soos Creek, a tributary, during low flows. Prior to October 1966, fish hatchery 0.5 mi upstream from station diverted up to 19 ft³/s which was returned downstream from the station.

Considered unregulated in the analyses presented in this report.

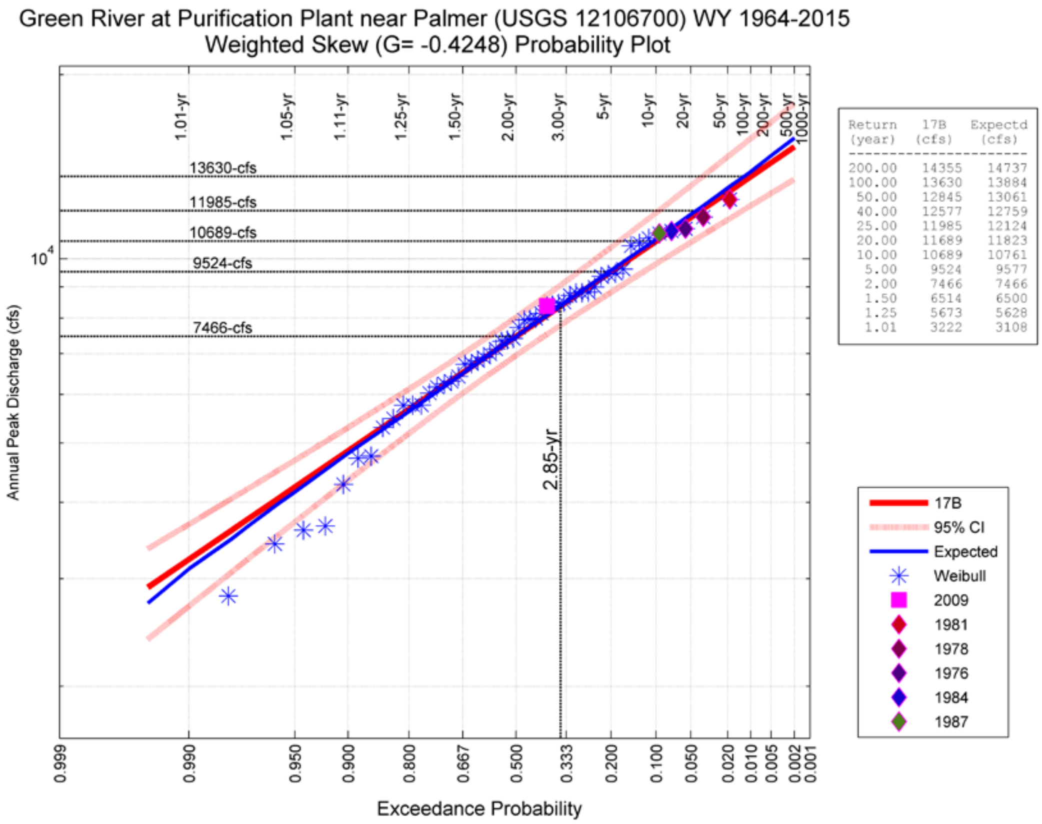


Figure B-18. Flood-frequency plot for the Green River at Purification Plant near Palmer streamflow gaging station 12106700, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - Since Dec. 5, 1961, flow regulated by Howard A. Hanson Reservoir (station 12105800), 4.1 mi upstream for flood control and during summer months to augment the natural river flow.

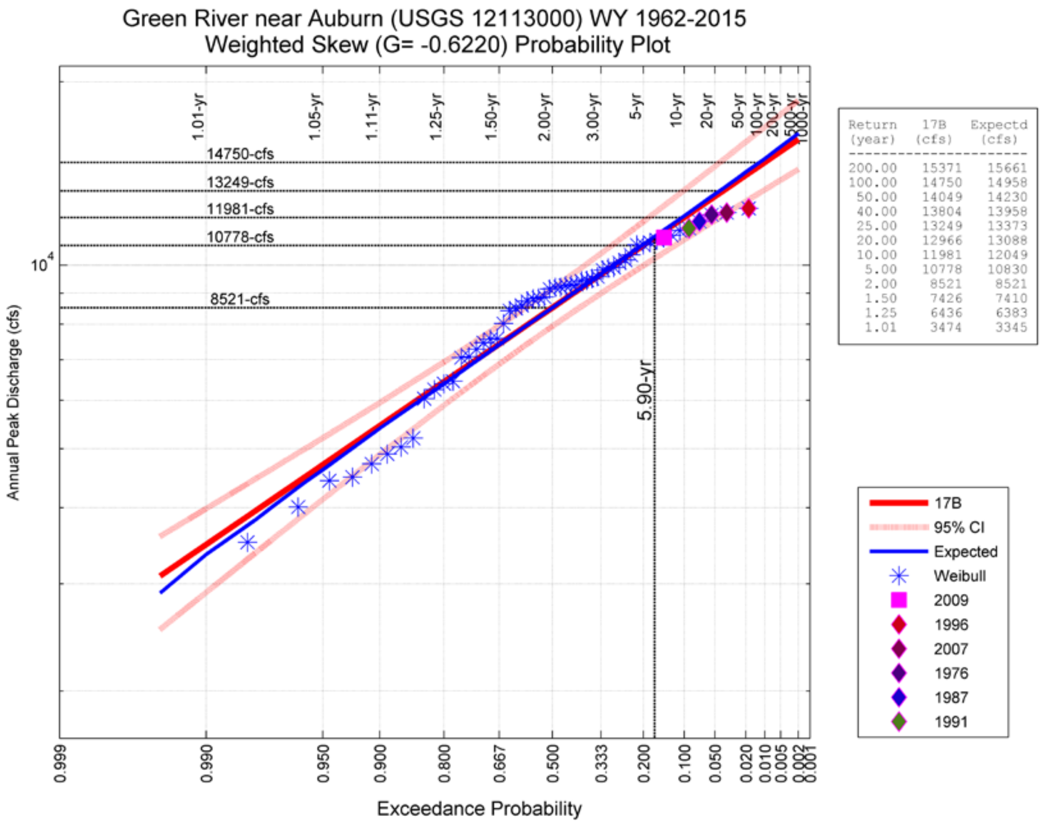


Figure B-19. Flood-frequency plot for the Green River near Auburn streamflow gaging station 12113000, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - Since Dec. 5, 1961, flow regulated by Howard A. Hanson Reservoir (station 12105800), 32.5 mi upstream from station, for flood control and during summer months, to augment the natural river flow. Minor diversions on upstream tributaries for domestic use.

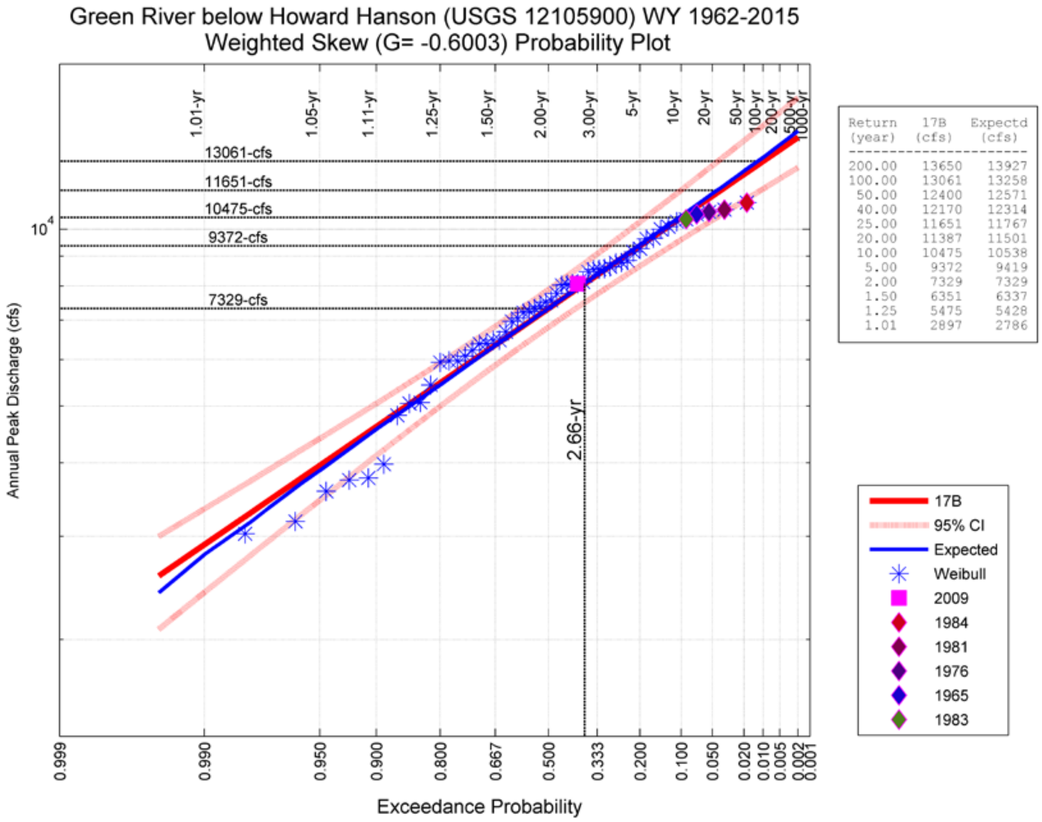


Figure B-20. Flood-frequency plot for the Green River below Howard Hanson streamflow gaging station 12105900, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - Flow regulated by Howard A. Hanson Reservoir (station 12105800) for flood control and during summer months to augment the natural river flow.

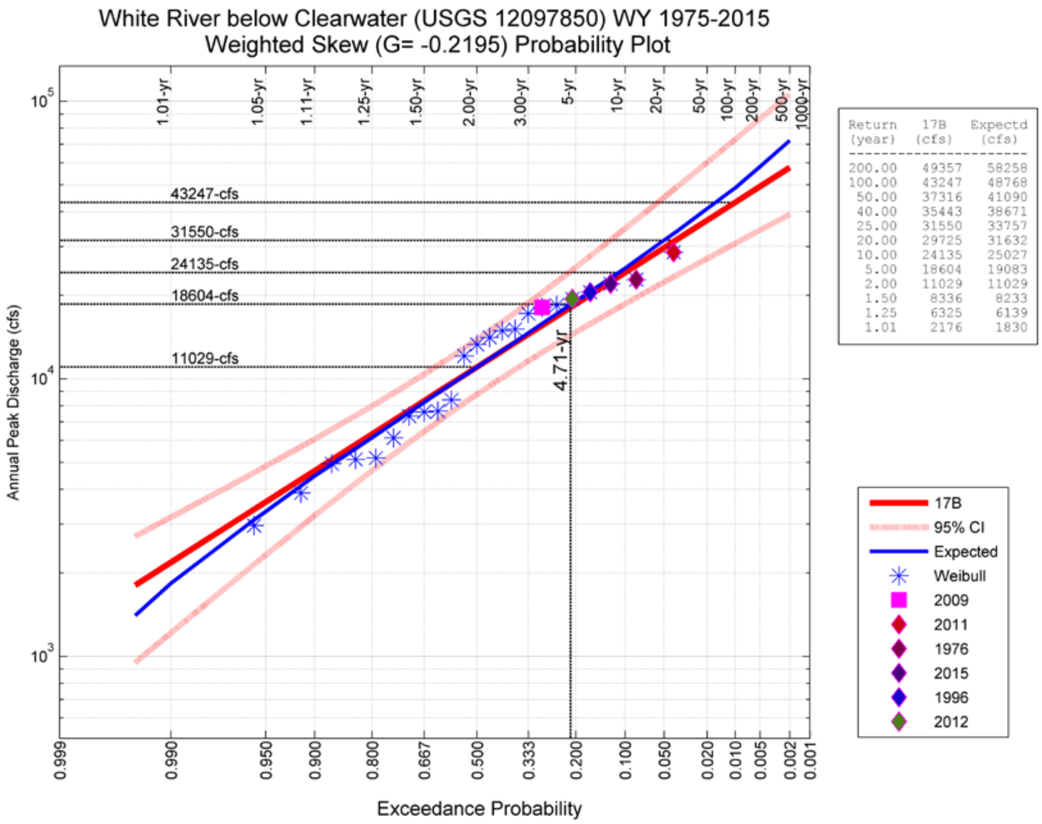


Figure B-21. Flood-frequency plot for the White River below Clearwater streamflow gaging station 12097850, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - No regulation or diversion upstream from station.

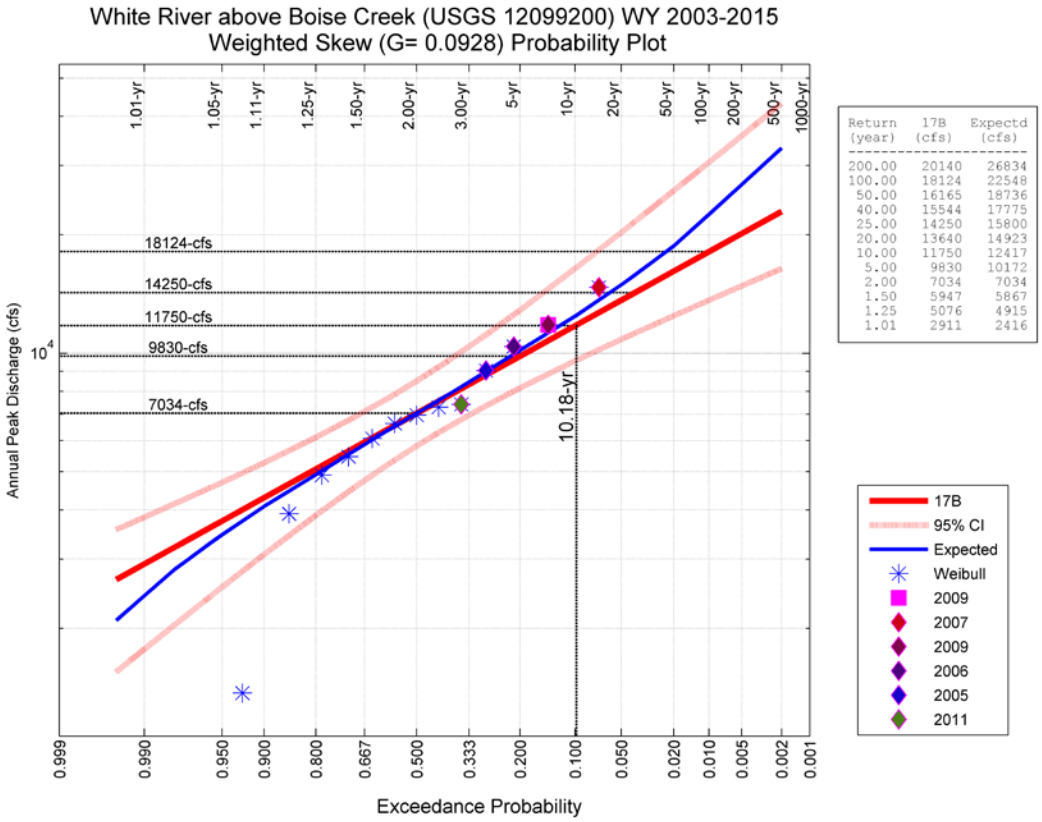
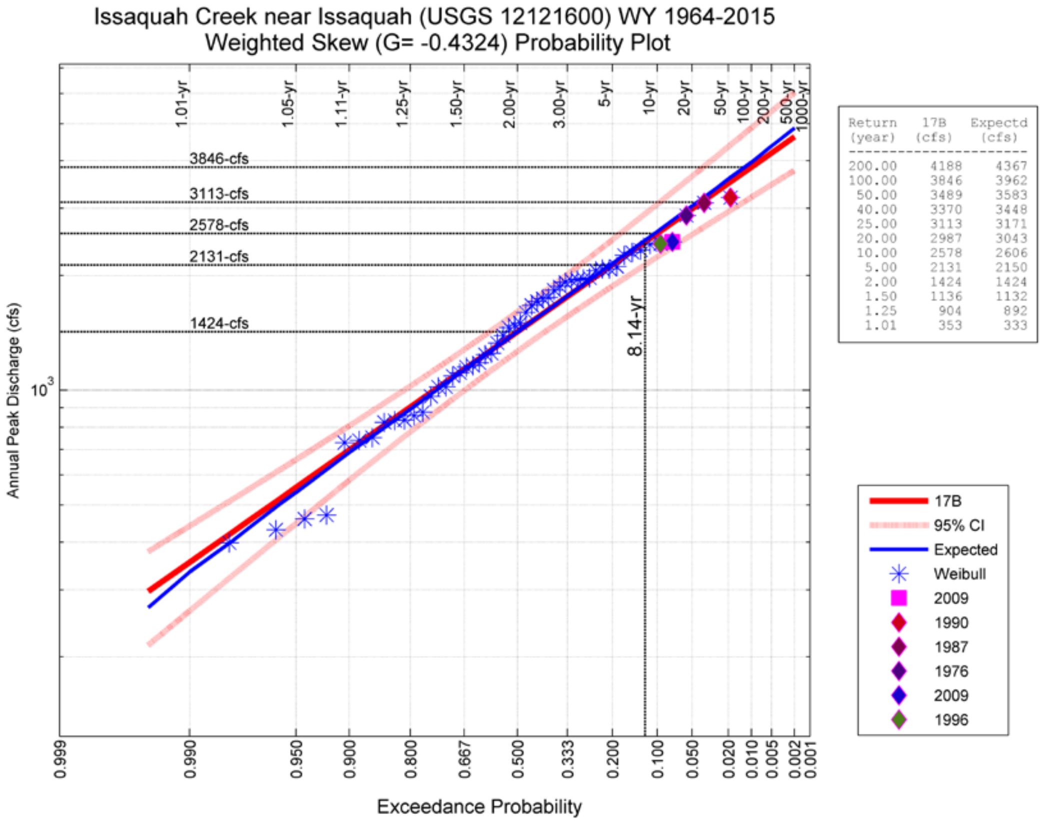


Figure B-22. Flood-frequency plot for the White River above Boise Creek streamflow gaging station 12099200, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - Since November 1911, White River Canal has diverted water from left bank, 1,500 ft upstream, for storage in Lake Tapps. Water is returned to the White River 20.3 mi downstream via Lake Tapps Diversion, after power development at Dieringer Powerplant. Since 1942, flows have been regulated by Mud Mountain Dam for flood control.



Return (year)	17B (cfs)	Expectd (cfs)
200.00	4188	4367
100.00	3846	3962
50.00	3489	3583
40.00	3370	3448
25.00	3113	3171
20.00	2987	3043
10.00	2578	2606
5.00	2131	2150
2.00	1424	1424
1.50	1136	1132
1.25	904	892
1.01	353	333

Figure B-23. Flood-frequency plot for the Issaquah Creek near Issaquah streamflow gaging station 12121600, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - Many minor diversions for irrigation and domestic use upstream from station.

Considered unregulated in the analyses presented in this report.

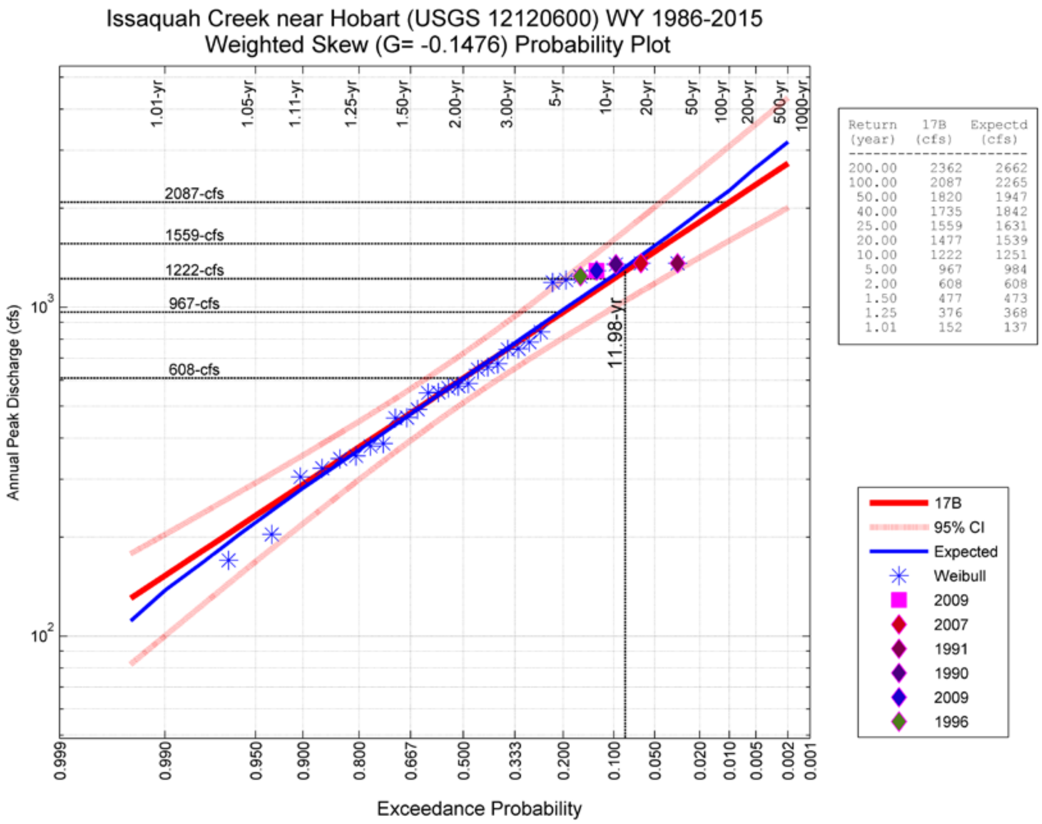
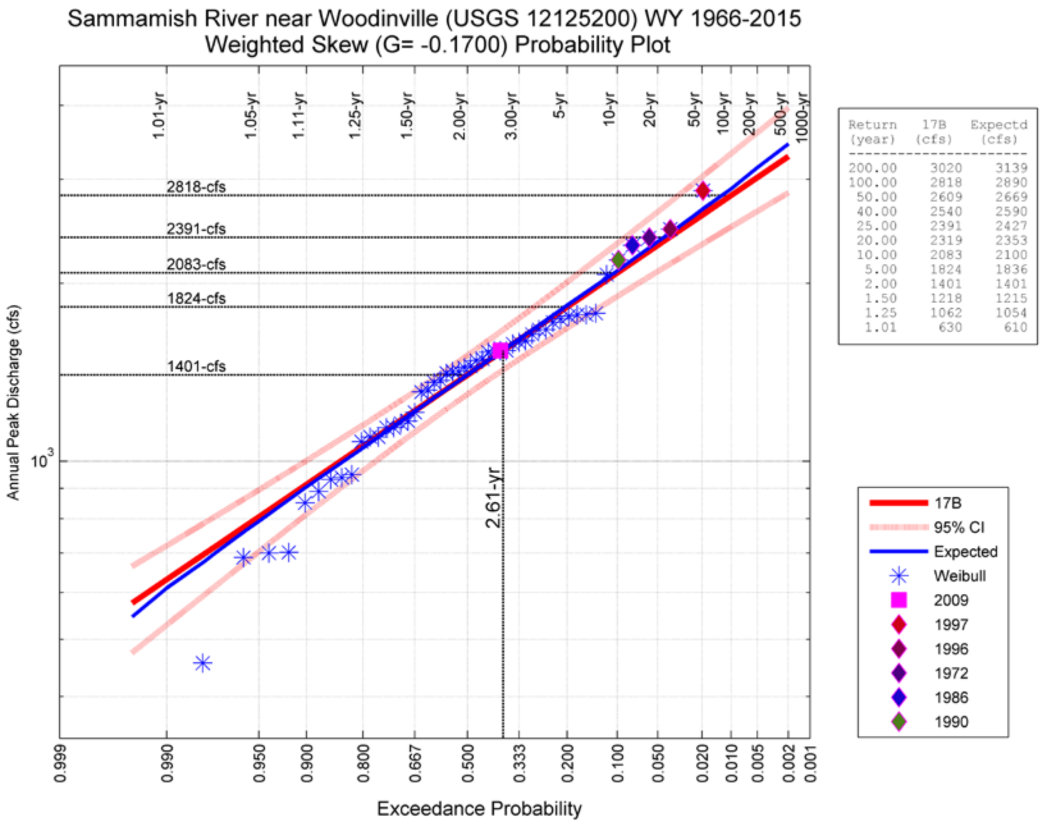


Figure B-24. Flood-frequency plot for the Issaquah Creek near Hobart streamflow gaging station 12120600, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - No known regulation or diversion upstream from station.



Return (year)	17B (cfs)	Expectd (cfs)
200.00	3020	3139
100.00	2818	2890
50.00	2609	2669
40.00	2540	2590
25.00	2391	2427
20.00	2319	2353
10.00	2083	2100
5.00	1824	1836
2.00	1401	1401
1.50	1218	1215
1.25	1062	1054
1.01	630	610

Figure B-25. Flood-frequency plot for the Sammamish River near Woodinville streamflow gaging station 12125200, showing the Log-Pearson Type III and Expected probability distributions and the annual peak discharges for the period of record through water 2015.

REMARKS - Records fair, except for those above 1,000 ft³/s which are poor. Some regulation at Sammamish Lake. Many small diversions for irrigation and domestic use.

Considered regulated in the analyses presented in this report.